Rare, exotic and invisible Higgs decays at the LHC

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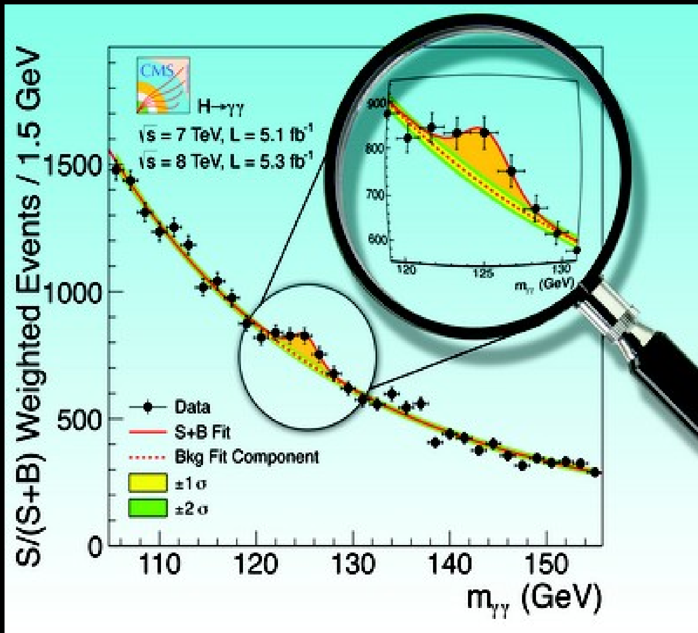
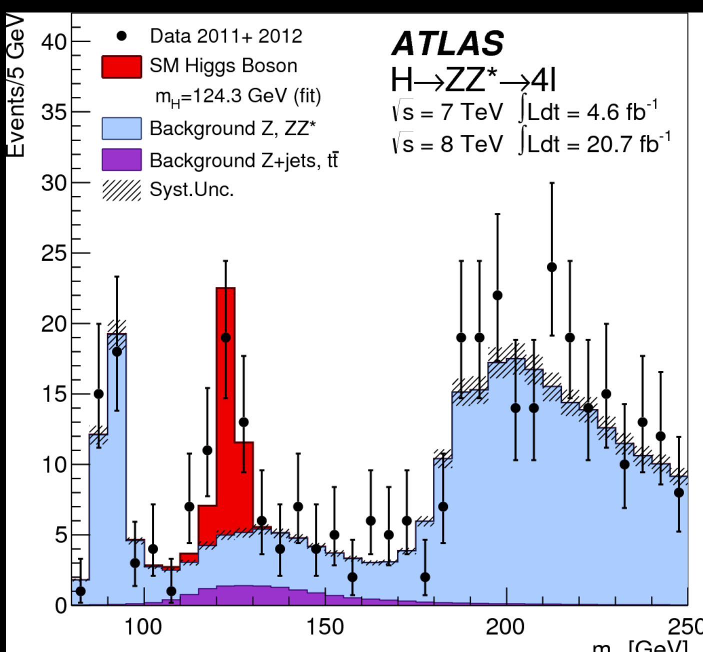
CERN

XIIth International Workshop on Interconnection between Particle Physics and Cosmology

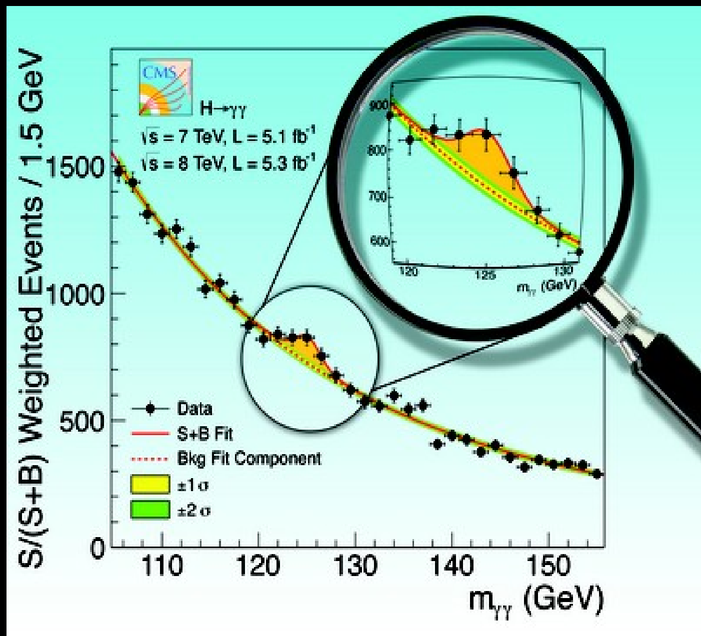
22.08.2018, Zürich



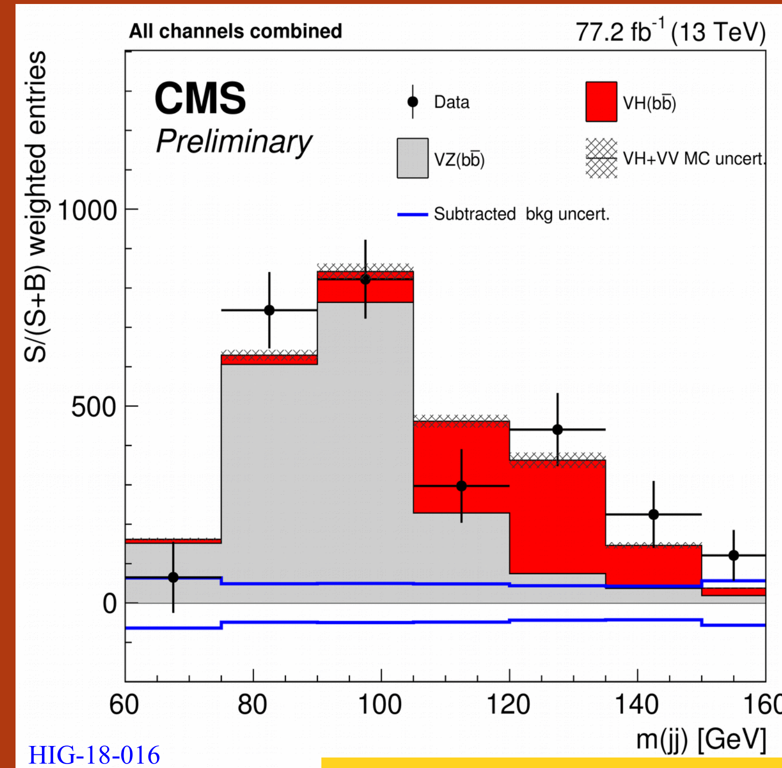
Hot news of 2012!



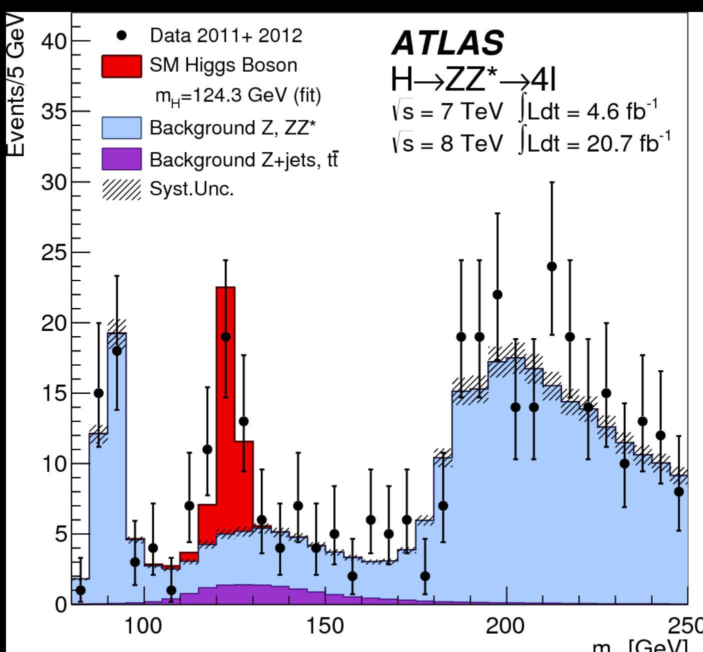
Thank you Higgs for all the fun over the six years!

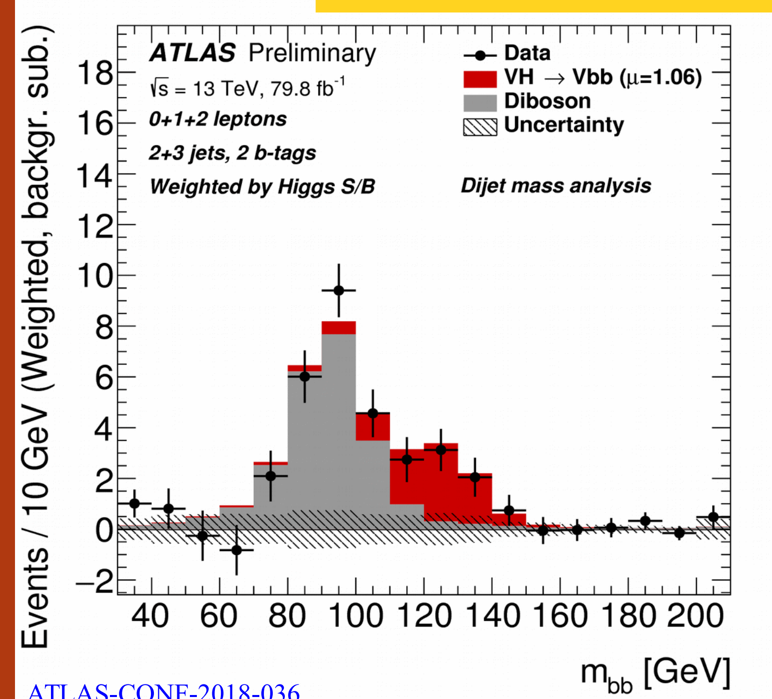


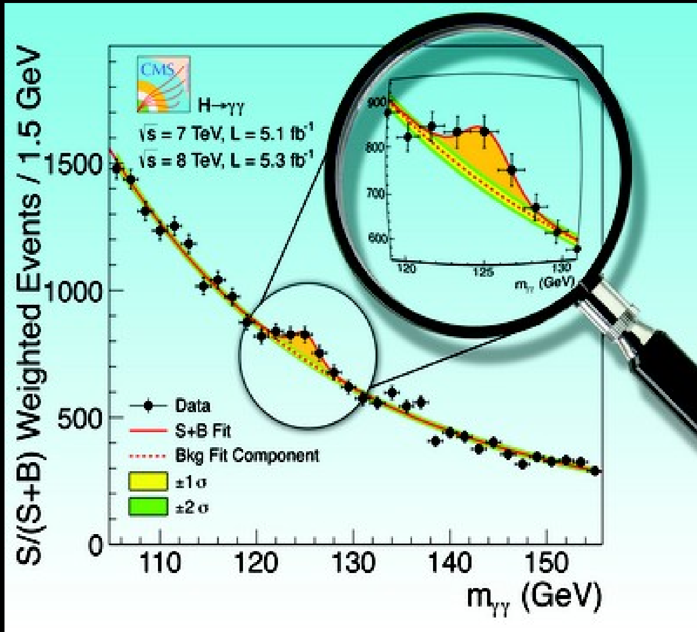
A journey for new discoveries!



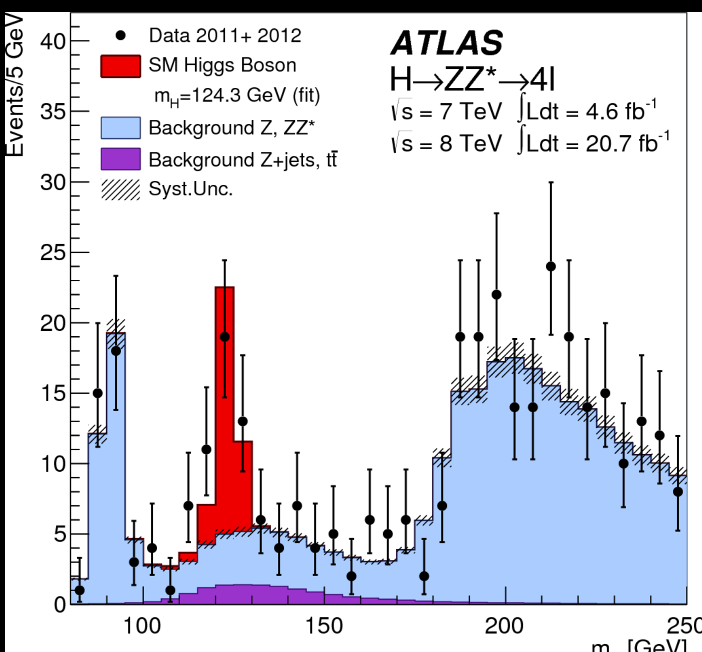
H→bb̄ Observed at the LHC!!

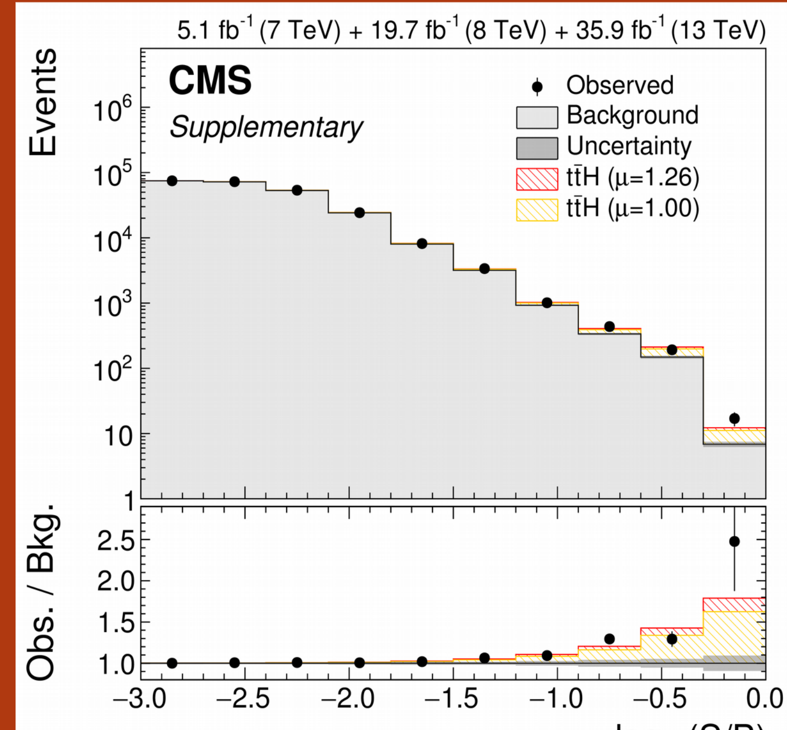






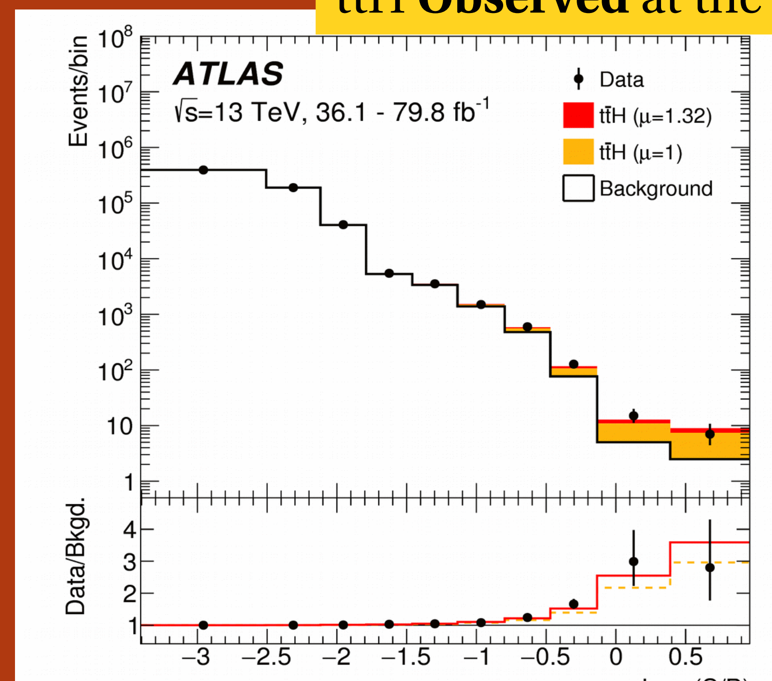
A journey for new discoveries!



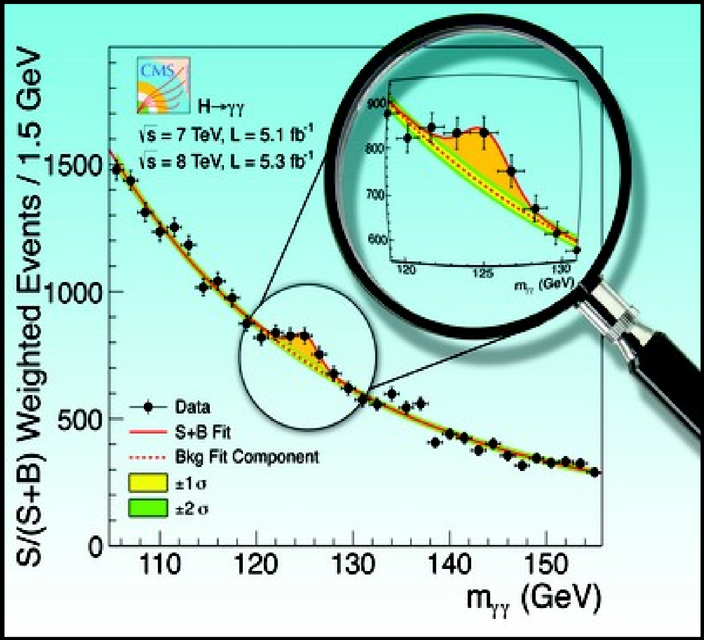


Phys. Rev. Lett. 120 (2018) 231801

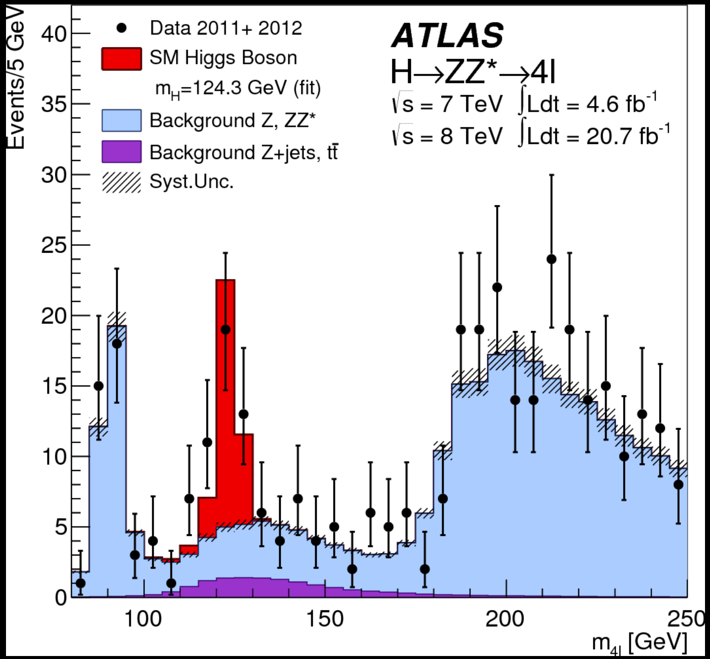
tt̄H **Observed** at the LHC!!

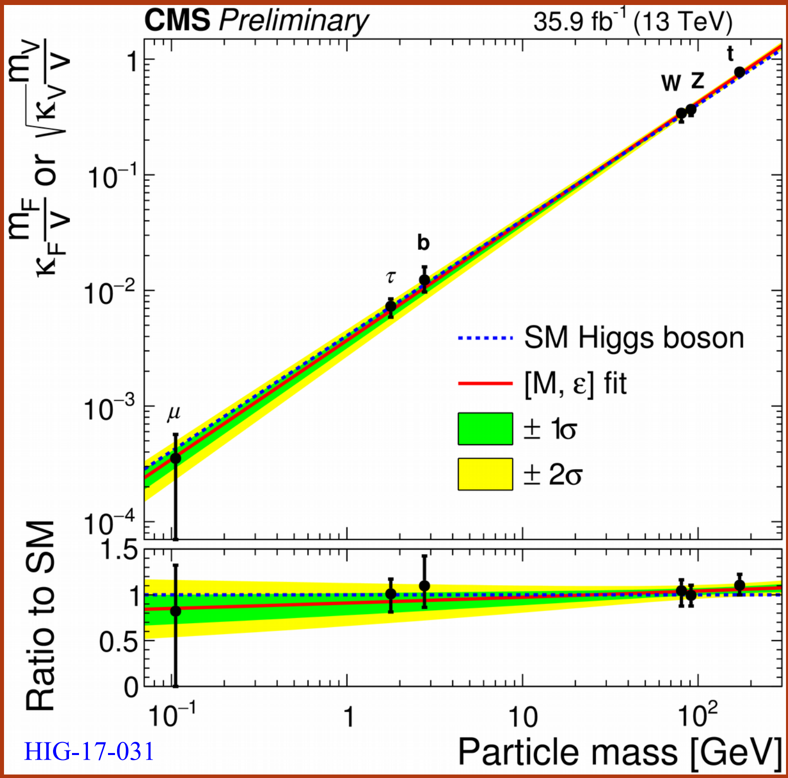


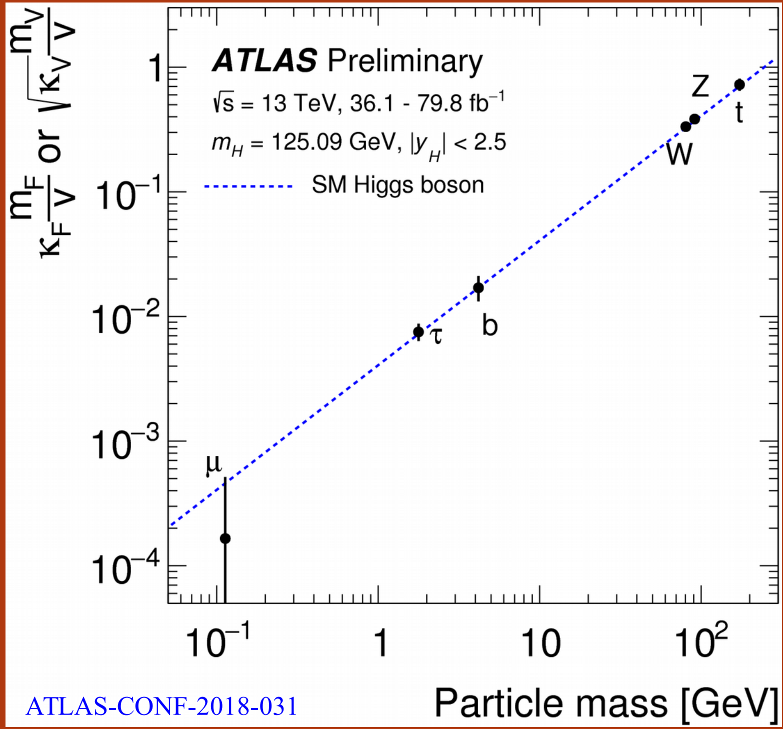
Phys. Lett. B 784 (2018) 173

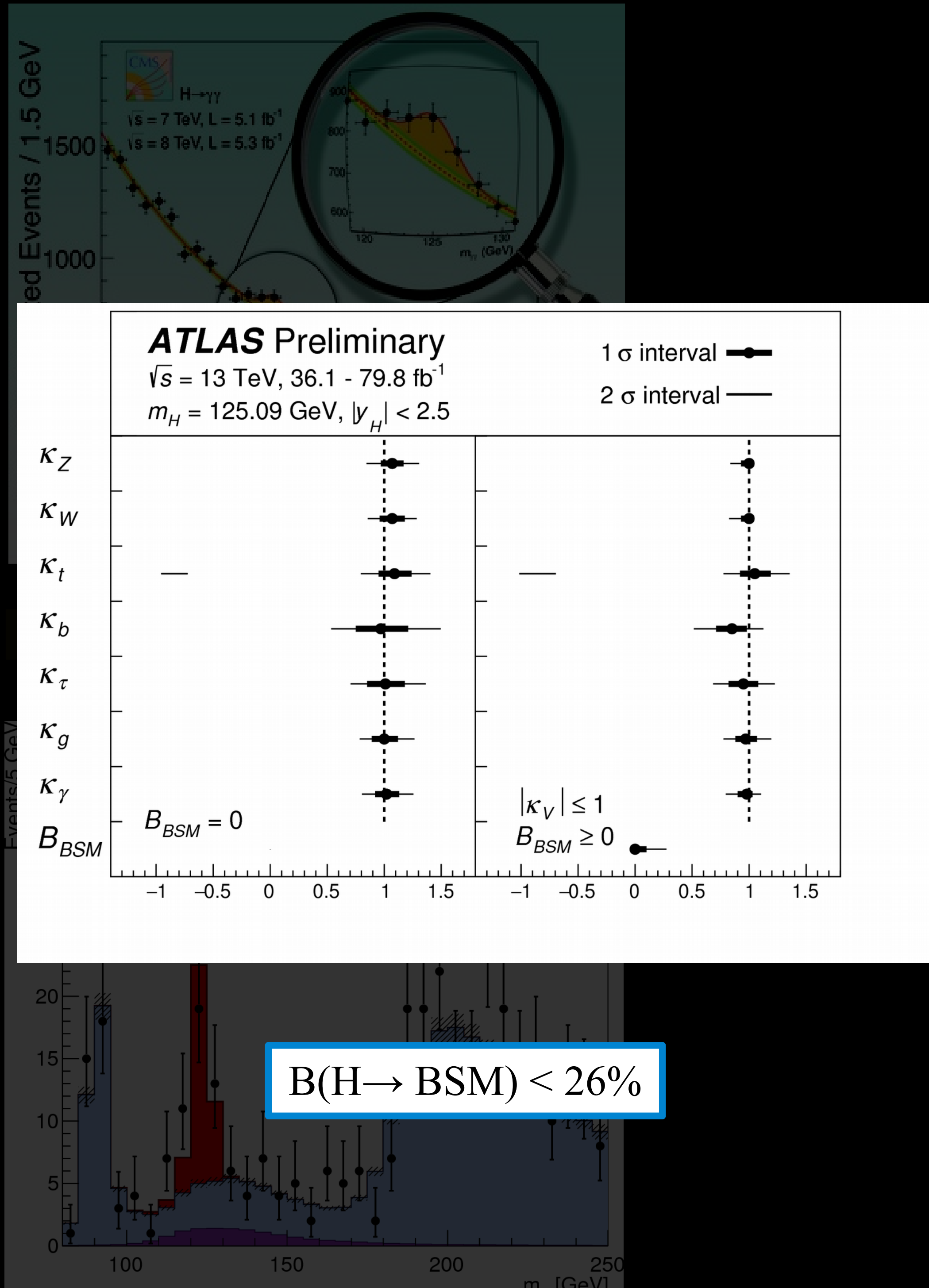


A journey towards precision

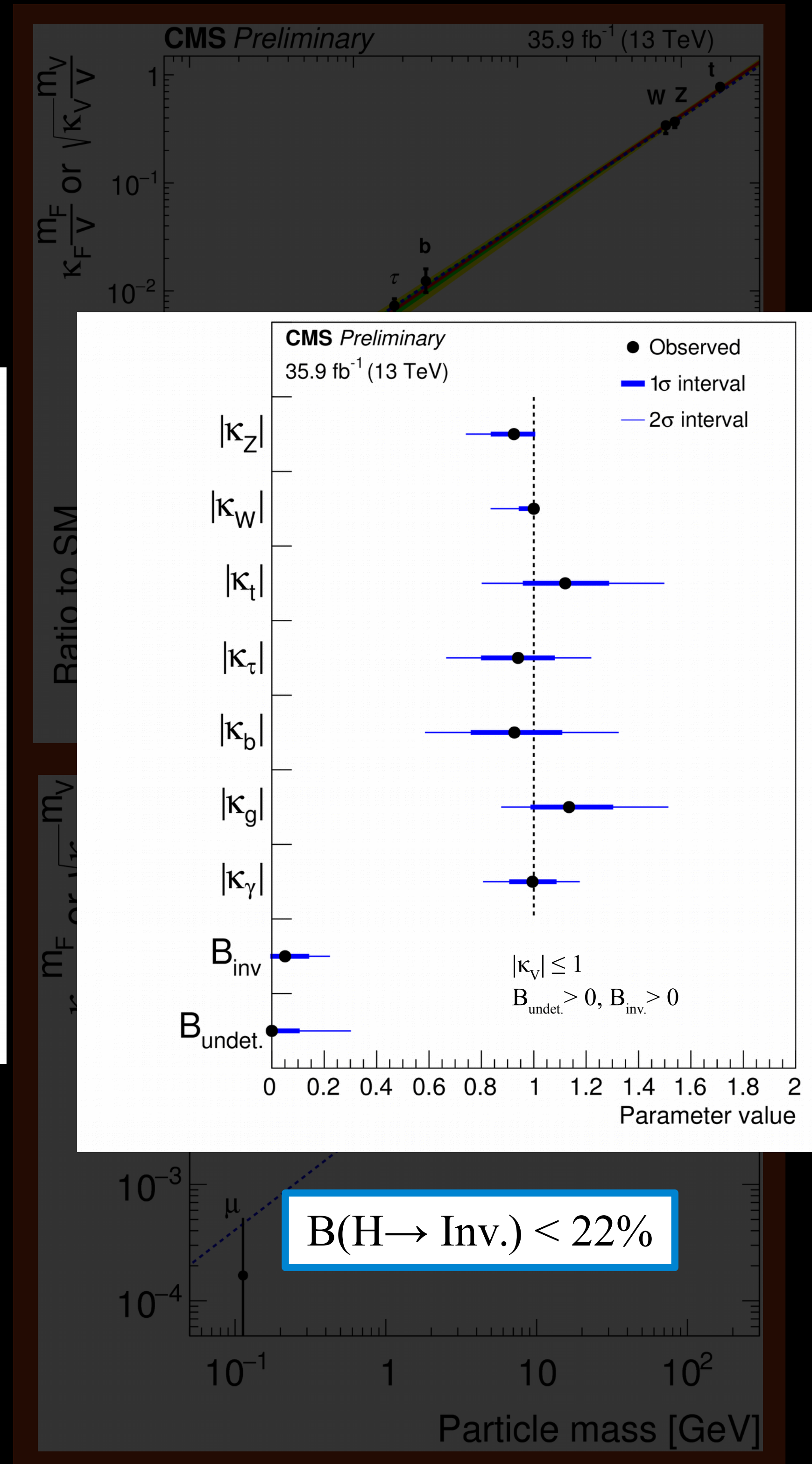




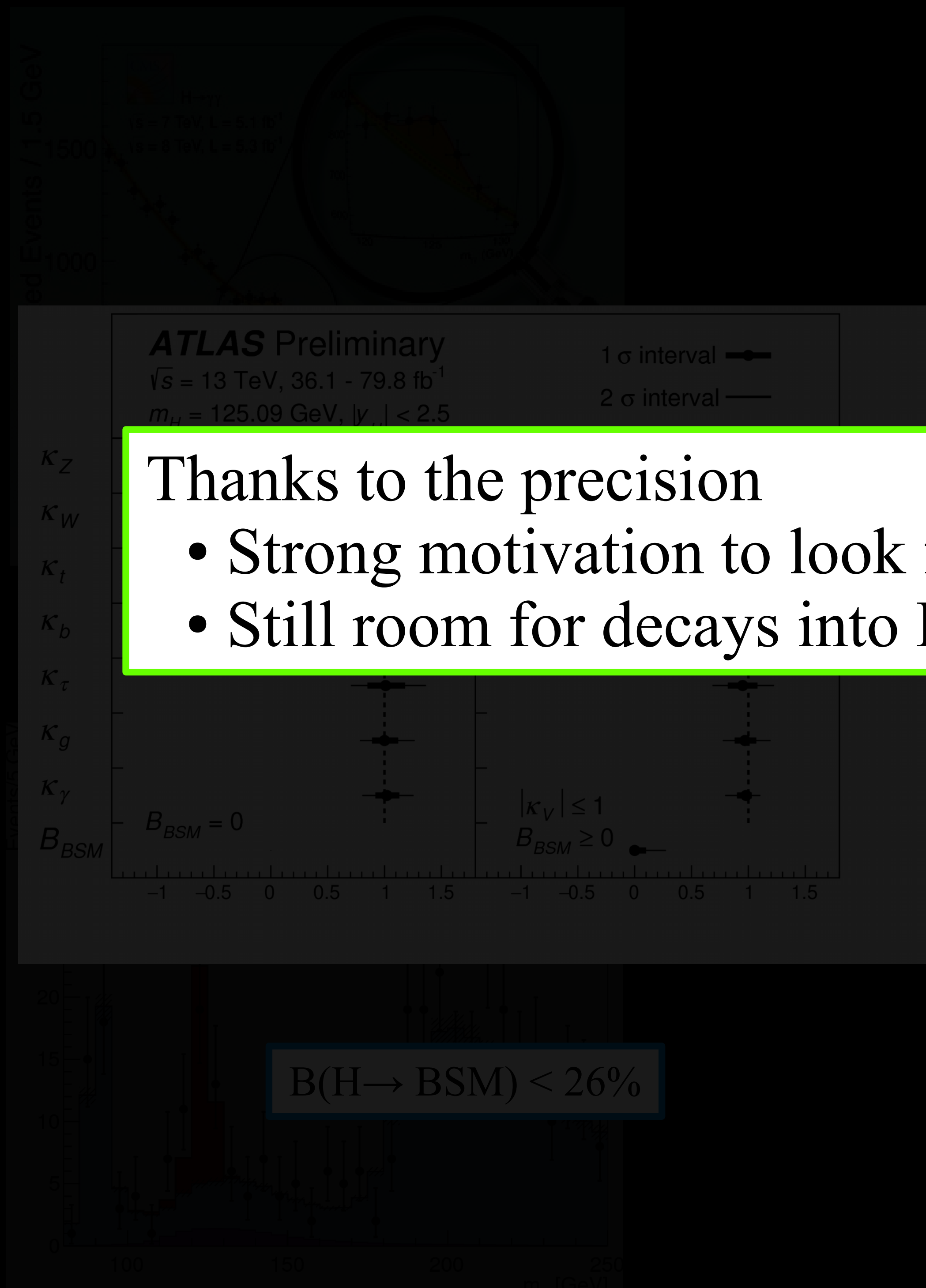


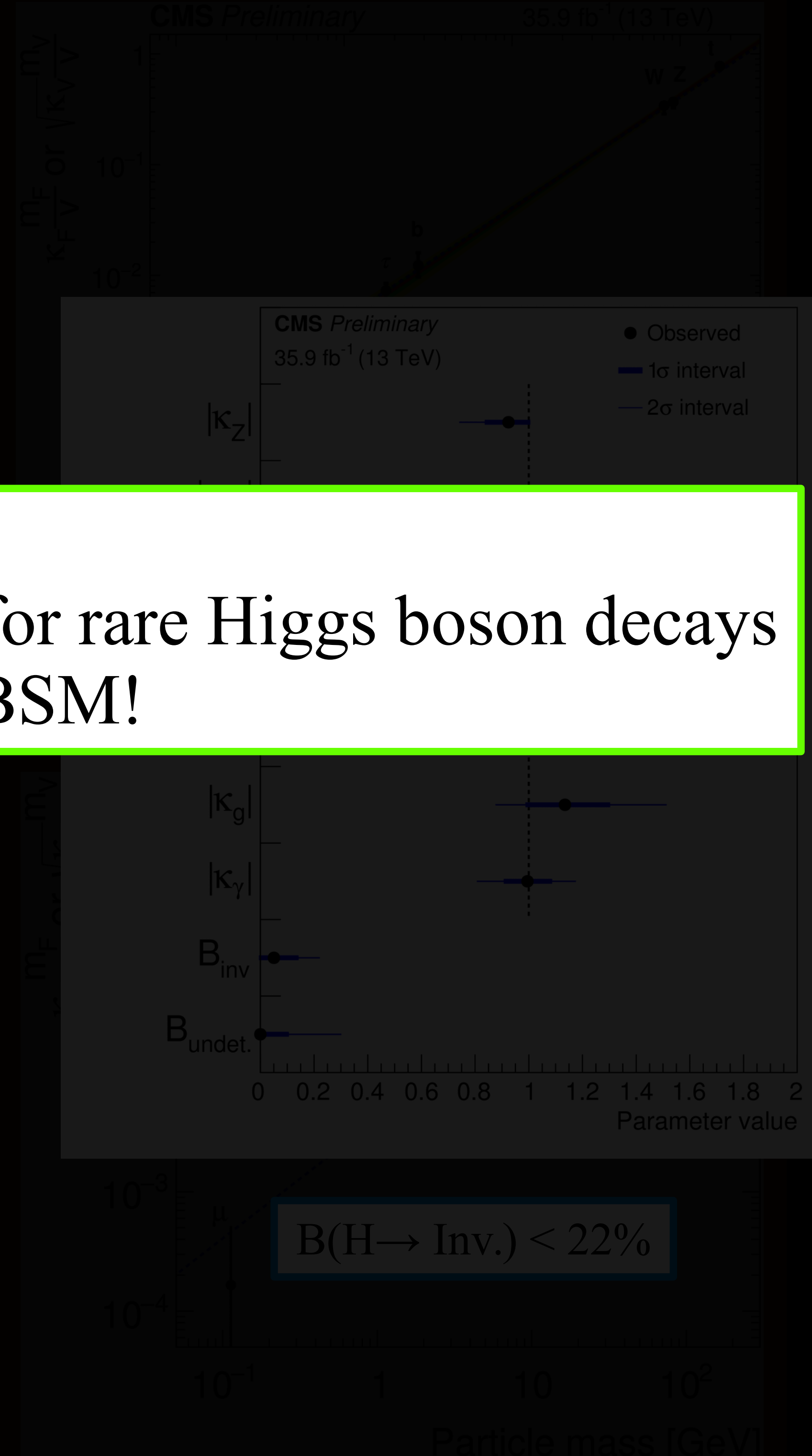


B(H→ BSM) < 26%



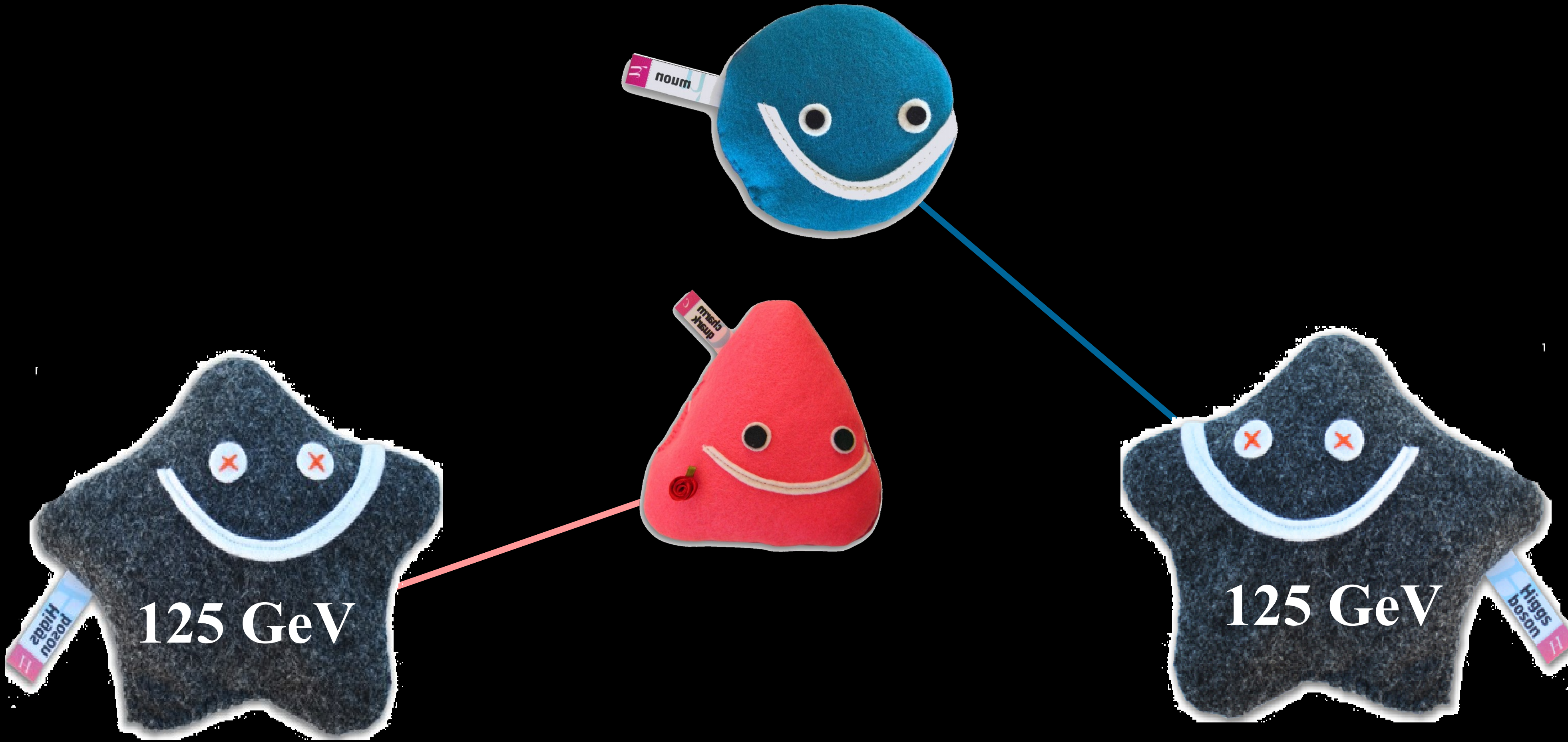
B(H→ Inv.) < 22%





Thanks to the precision

- Strong motivation to look for rare Higgs boson decays
- Still room for decays into BSM!



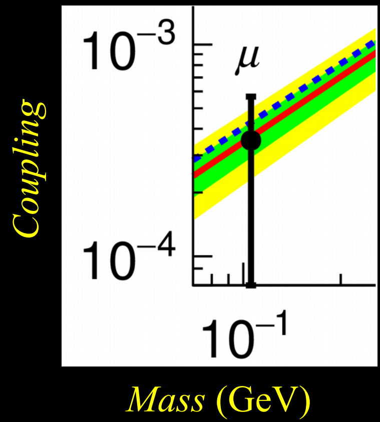
HIGGS RARE DECAYS

Coupling to 2nd generation fermions

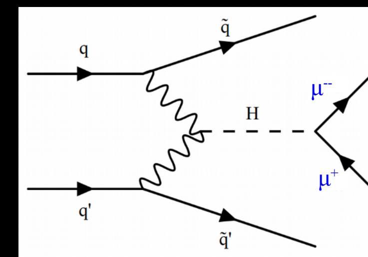
Higgs decay to muons

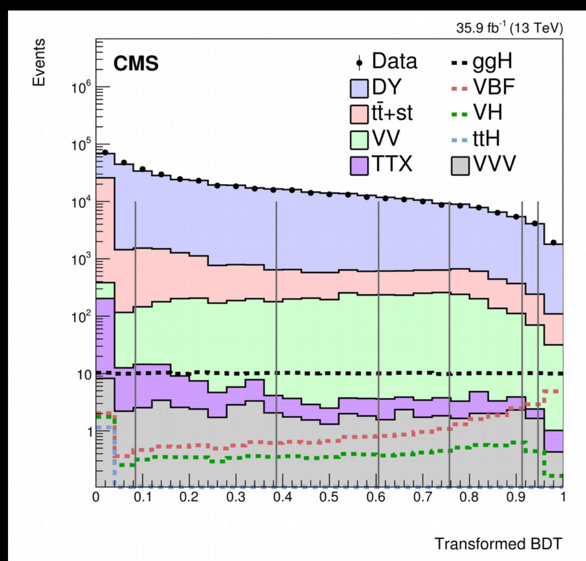
ATLAS-CONF-2018-026

arXiv:1807.06325
Submitted to PRL

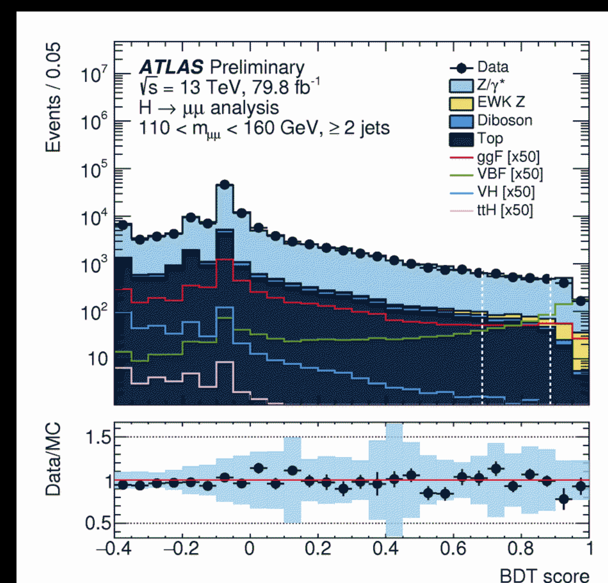


- A rare process: B(H→ μμ) = 0.022%
- Main targets: VBF and ggH
- Selection based on two muons and additional jets
- Categorization: event kinematics (BDT) and $m_{\mu\mu}$ resolution





Trained for *all signals*



Trained for *VBF*

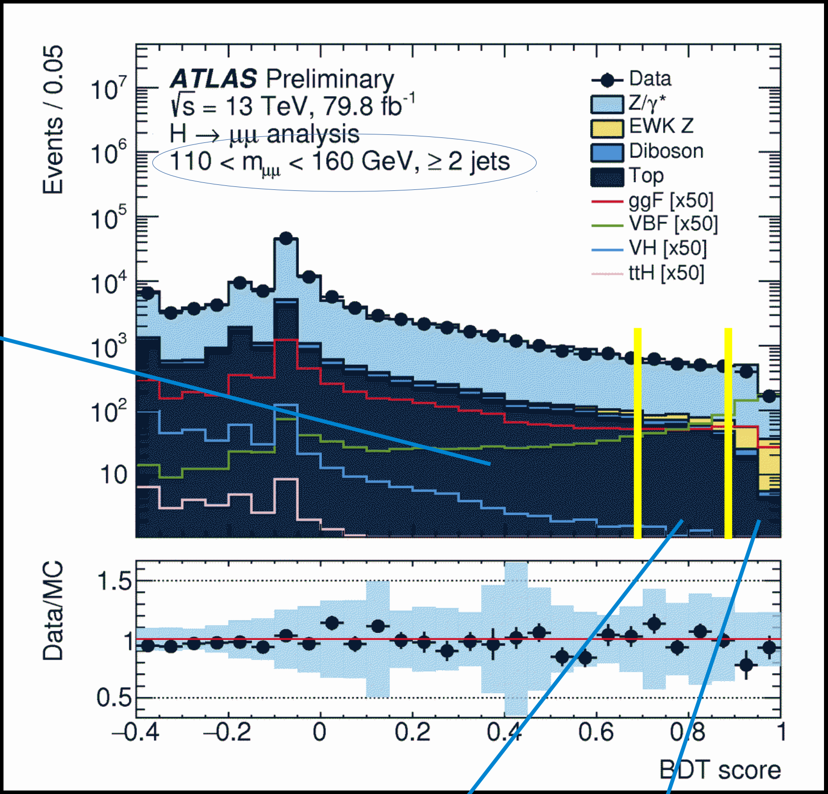
Higgs decay to muons

ATLAS EXPERIMENT
ATLAS-CONF-2018-026

CMS
arXiv:1807.06325
Submitted to PRL

ggH tags:

- Includes also events with < 2 jets
- 3 regions based on $p_T^{\mu\mu}$
  → control the remnant of DY
- Further divided by 2 based on η_μ
  → $m_{\mu\mu}$ resolution

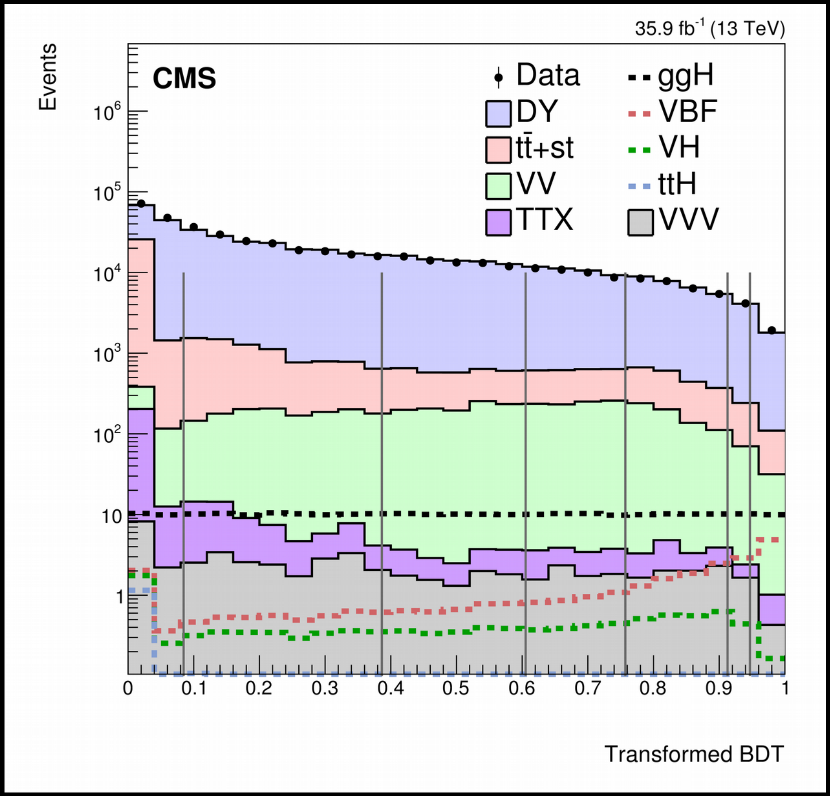


Tight and loose VBF tags

Higgs decay to muons

ATLAS-CONF-2018-026

arXiv:1807.06325
Submitted to PRL



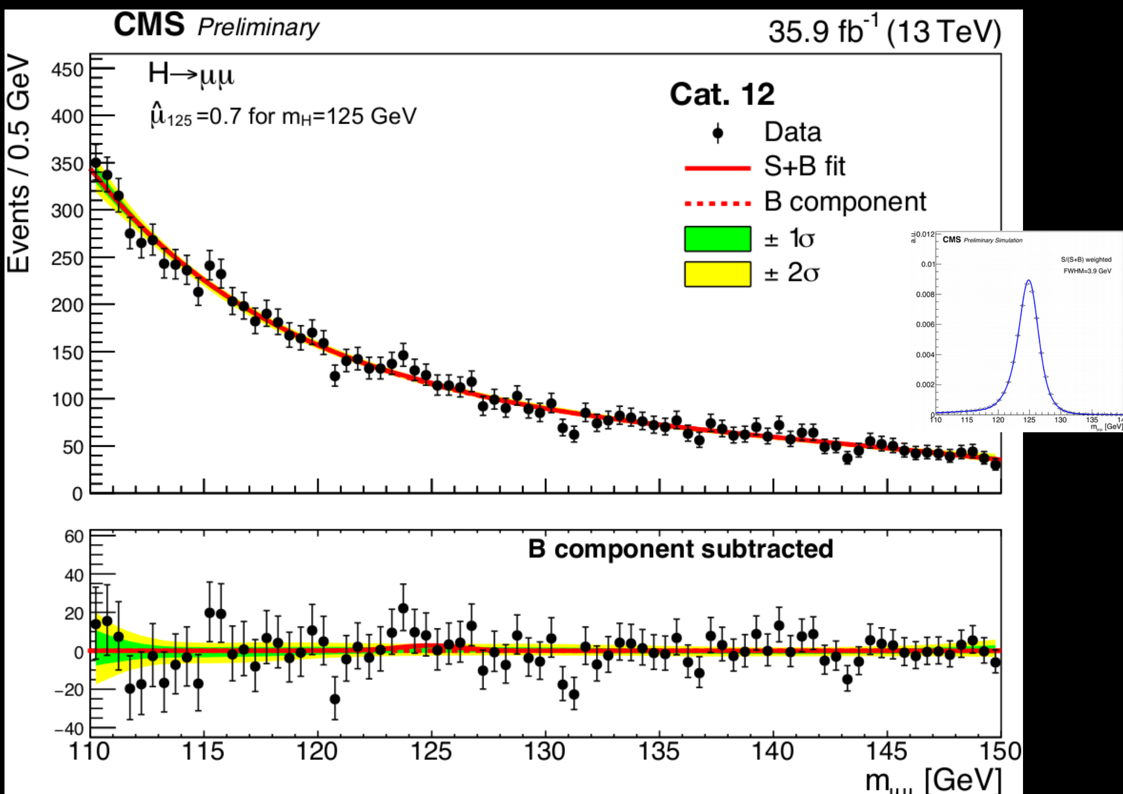
- BDT transformed for a uniform signal contribution
- Categories with enough yield, subdivided in 3 regions based on η_μ $\rightarrow m_{\mu\mu}$ resolution

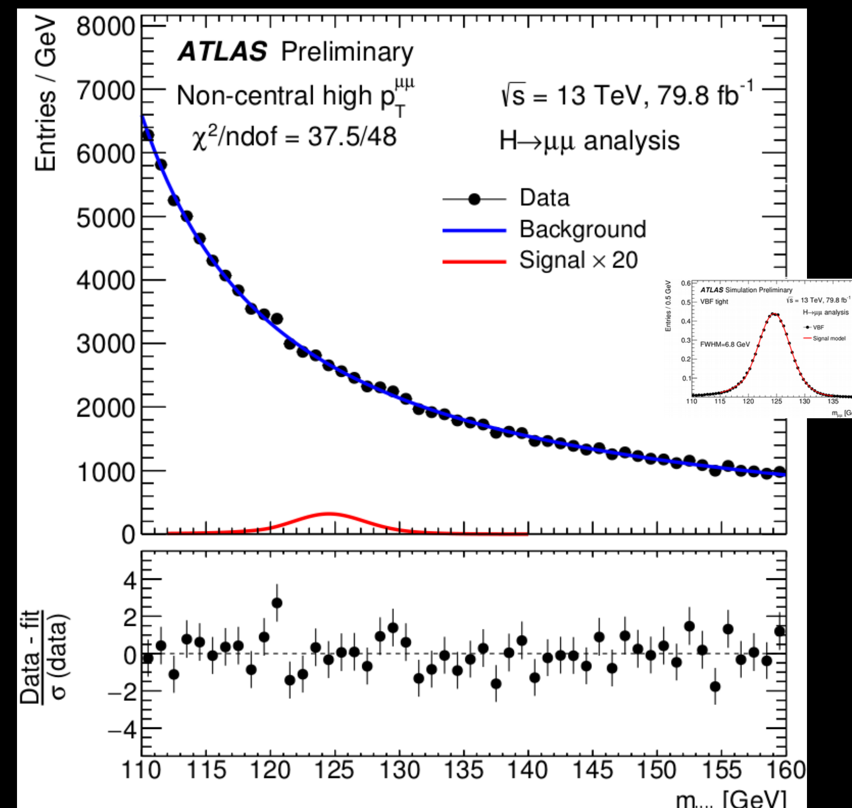
Higgs decay to muons

ATLAS-CONF-2018-026

arXiv:1807.06325
Submitted to PRL

- Parametric models for signal and falling $m_{\mu\mu}$ background
- The effect of spurious signal and the bias on background models are taken as systematics uncertainties
- Simultaneous fit to all categories

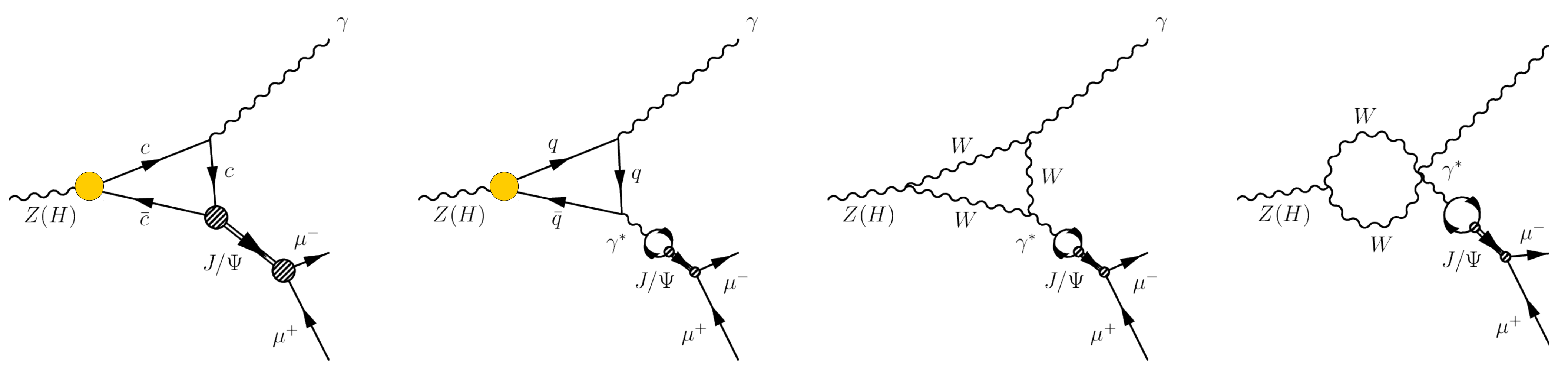




Observed (expected) UL on σ×B(H→μμ)
2.95 (2.45) × SM

Observed (expected) UL on σ×B(H→μμ)
2.1 (2.0) × SM

Higgs decay to *M*γ



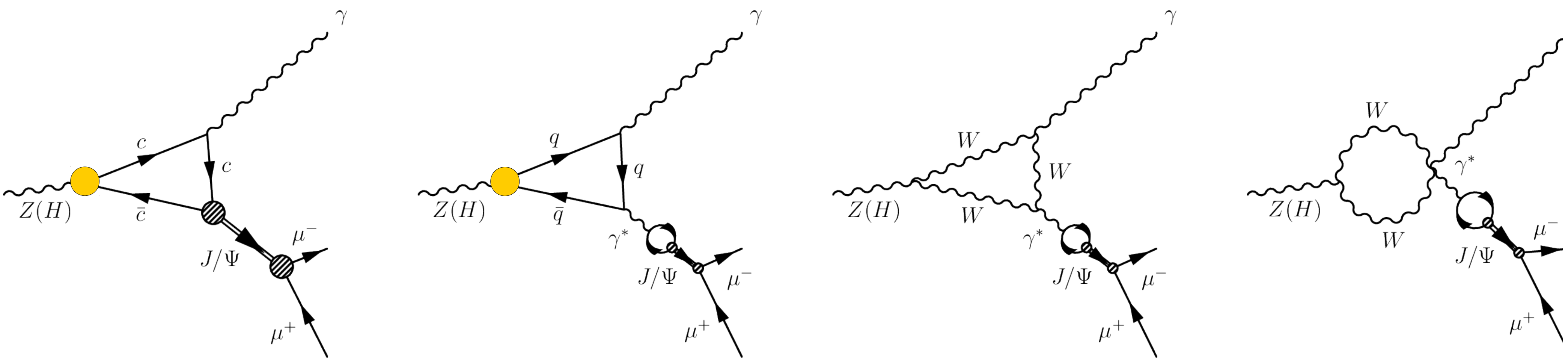
Probing the Higgs coupling with light and c quarks!

- Complementary to direct $H \to c\bar{c}$ searches
- The LHC direct limit on $\sigma_{ZH} \times B(H \to c\bar{c})$ is ~100×SM

ATLAS EXPERIMENT PRL120 (2018) 211802

H→ *M*γ at LHC 13 TeV		
$H \to \varphi\gamma \to K^+K^-\gamma$	ATLAS EXPERIMENT JHEP 07(2018) 127	
$H \to \rho\gamma \to \pi^+\pi^-\gamma$	ATLAS EXPERIMENT JHEP 07(2018) 127	
$H \to \psi/\Upsilon\gamma \to \mu^+\mu^-\gamma$	ATLAS EXPERIMENT arXiv:1807.00802	CMS CMS-SMP-17-012

Higgs decay to $M\gamma$



Probing the Higgs coupling with light and c quarks!

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ATLAS PRL120 (2018) 211802

$H\to M\gamma$ at LHC 13 TeV		
$H\to\varphi\gamma\to K^+K^-\gamma$	ATLAS JHEP 07(2018) 127	
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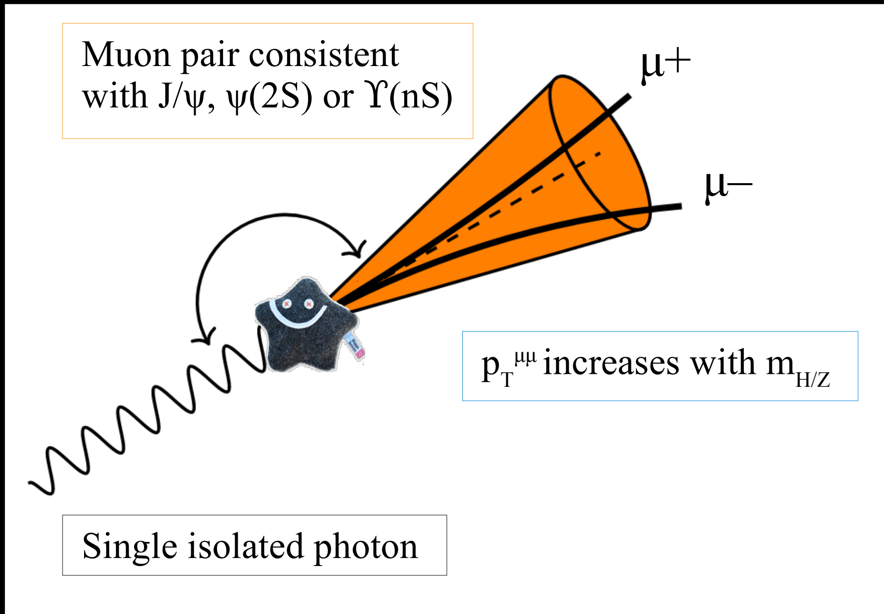
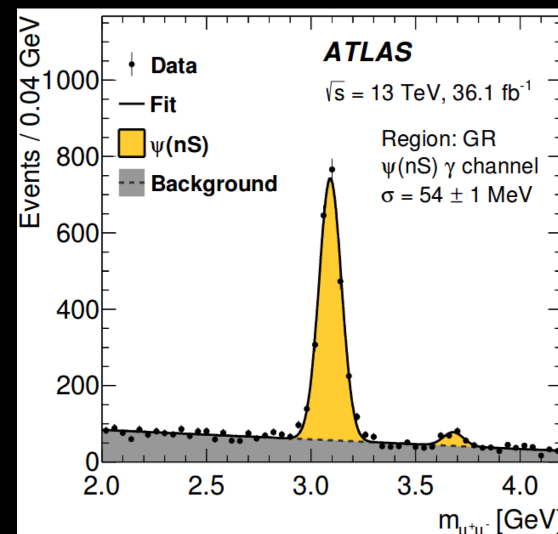
Higgs decay to *M*γ

arXiv:1807.00802



- Signal extraction: 2D fit of $m_{\mu\mu\gamma}$ and $m_{\mu\mu}$
- Signal model: parametric, from simulation
- Background model: non-parametric from data

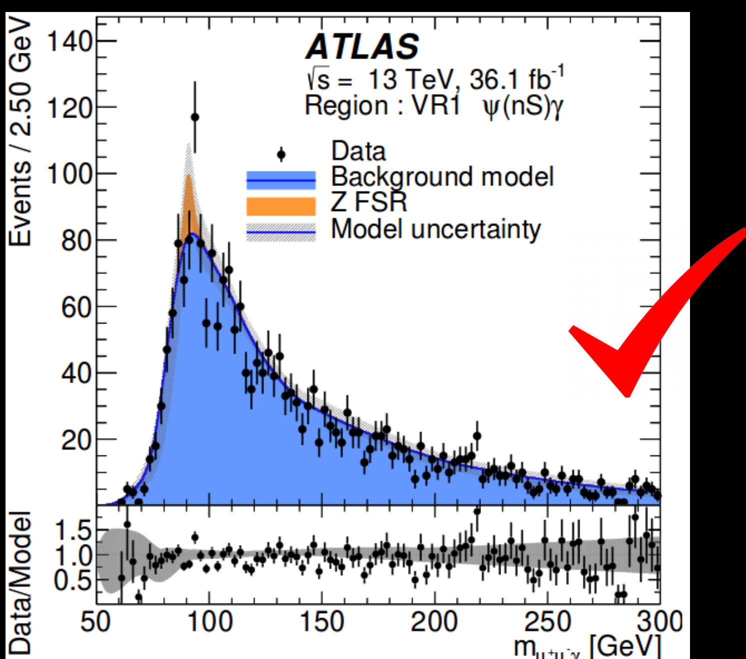
*M*γ candidates in data with looser isolation and $p_T^{\mu\mu}$



Used to generate pseudo-data

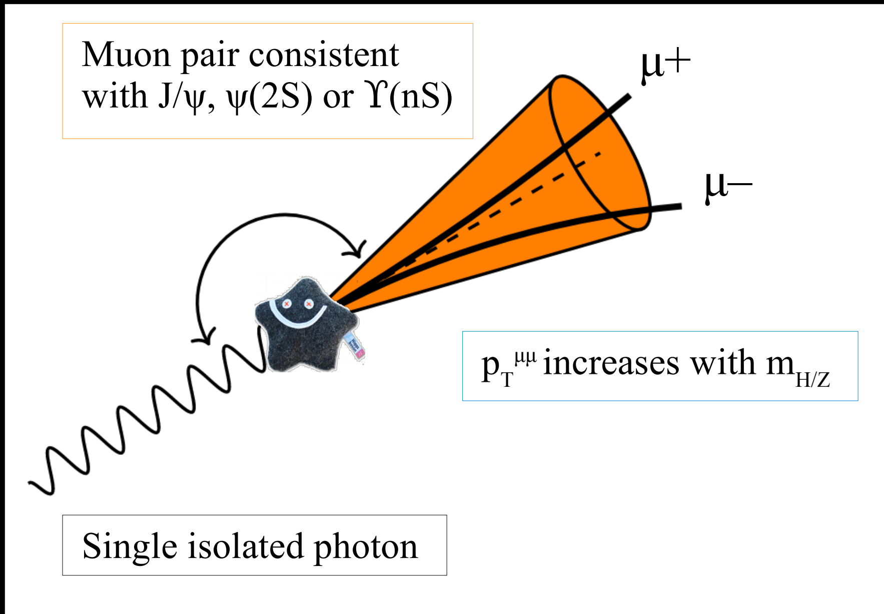
Apply all selections! $m_{\mu\mu\gamma}$ smoothed

Validated in other regions



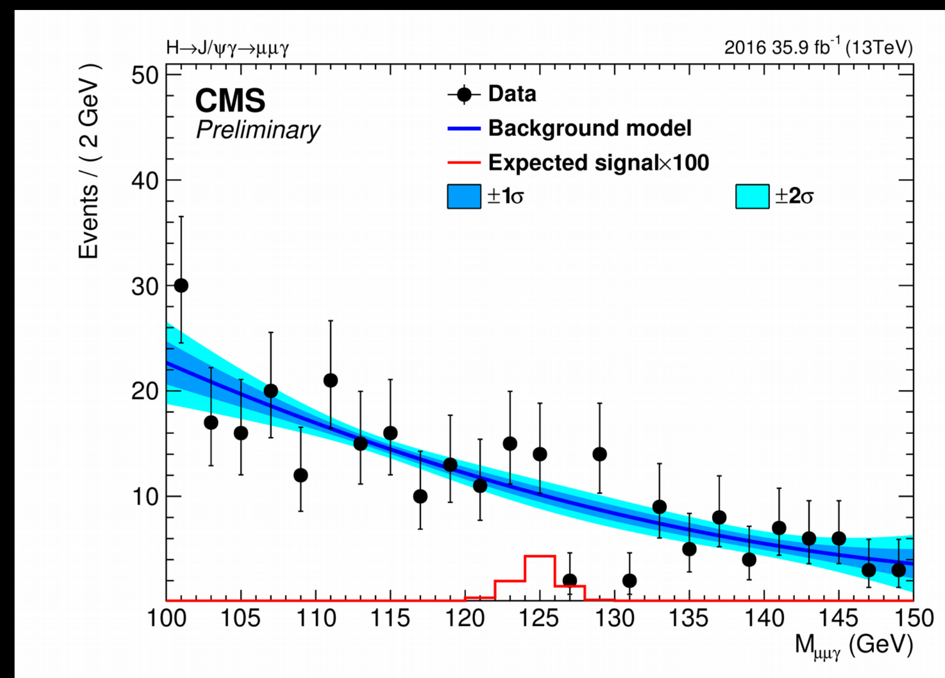
Higgs decay to J/Ψγ

SMP-17-012



- Signal extraction: bump-hunt over $m_{\mu\mu\gamma}$
- Signal model: parametric, from simulation
- Background model: parametric from data
  - Negligible bias from the model choice

Decay	Category Production	Data	Signal	Background Peaking!
$H \to J/\psi\ \gamma$	ggF	279	7.1×10^{-2}	0.2
	VBF		3.5×10^{-3}	9.4×10^{-3}
	ZH		7.1×10^{-4}	2.3×10^{-3}
	W^+H		6.0×10^{-4}	1.0×10^{-3}
	W^-H		4.5×10^{-4}	1.3×10^{-3}
	ttH		2.7×10^{-4}	1.3×10^{-3}



Signal peak overwhelmed by H→ ℓℓγ!!

Higgs decay to $M\gamma$

CMS SMP-17-012

ATLAS EXPERIMENT arXiv:1807.00802

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$ SM: 10^{-6}	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$ SM: 10^{-9}	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7

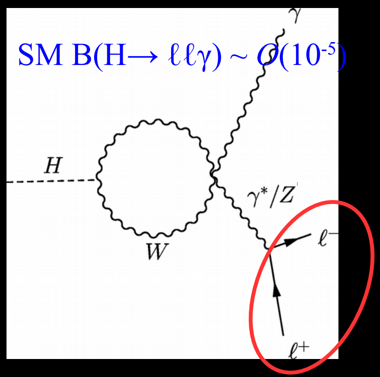
The first result!

Observed (expected) upper limits at 95% CL

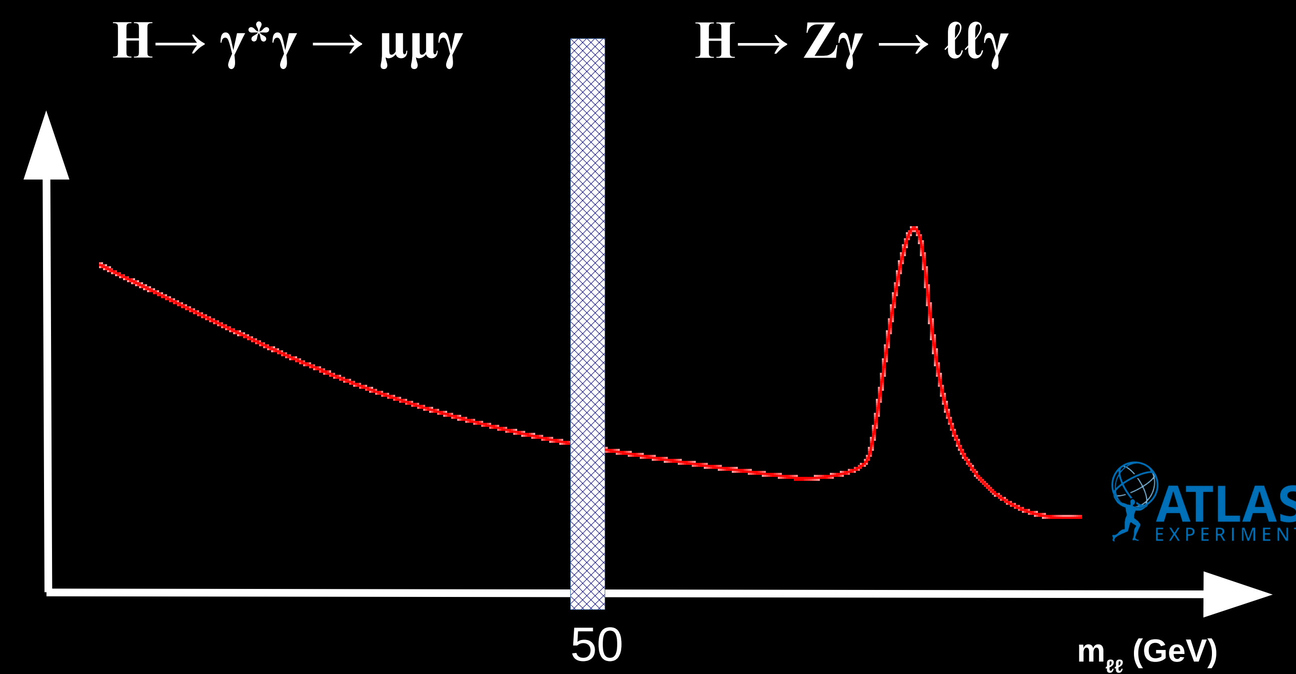
Channel	$\sigma(fb)$ *	$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\,\gamma)$	$\frac{\mathcal{B}(\mathrm{Z(H)} \to \mathrm{J}/\psi\,\gamma)}{\mathcal{B}_{SM}(\mathrm{Z(H)} \to \mathrm{J}/\psi\,\gamma)}$
$\mathrm{H} \to \mathrm{J}/\psi\,\gamma$	$2.5\ (1.7^{+0.8}_{-0.5})$	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$	260 (170)

* : $\sigma(\mathrm{pp} \to \mathrm{H(Z)} \to (\mathrm{J}/\psi \to \mu\mu)\gamma)\ (fb)$

Higgs decay to $\ell\ell\gamma$



A rare process with $B(H\to\ell\ell\gamma) \sim O(10^{-5})$

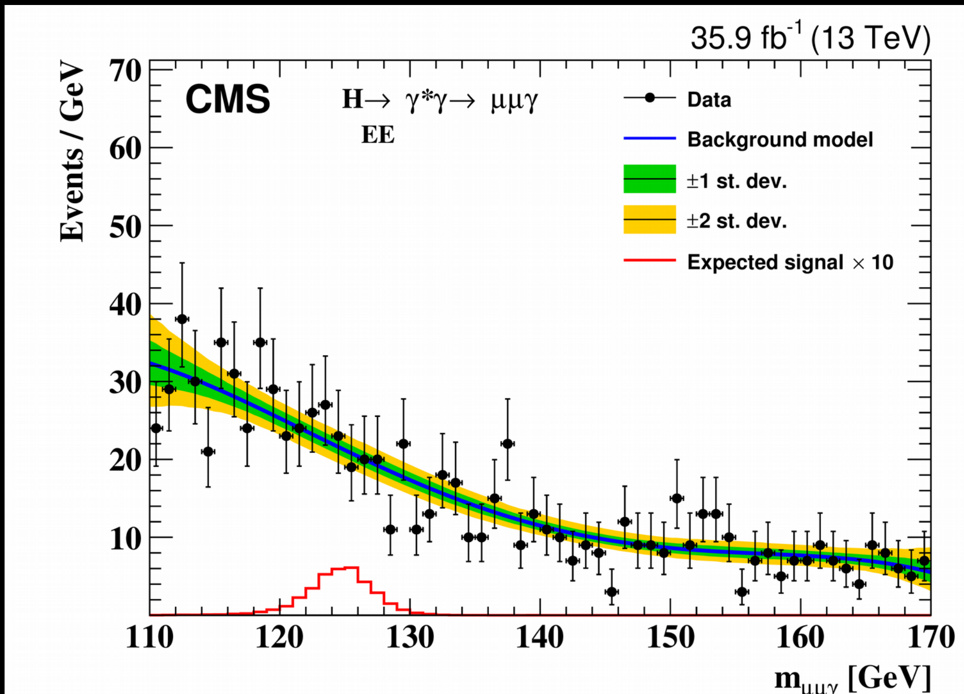


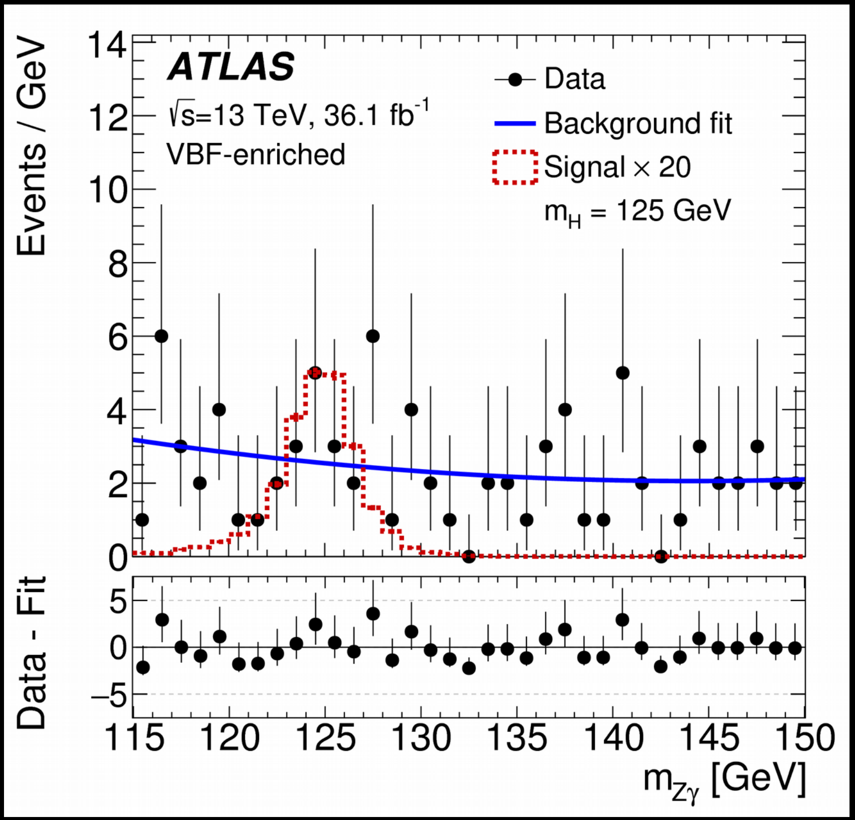
Similar approaches in the two experiments

- Event categorization based on signal purity and $m_{\ell\ell\gamma}$ resolution
- Bump-hunting over the $m_{\ell\ell\gamma}$ spectrum
  - Parametric models for signal peak
  - Parametric model for backgrounds from data

Higgs decay to $\ell\ell\gamma$

arXiv:1806.05996
Sub. to JHEP





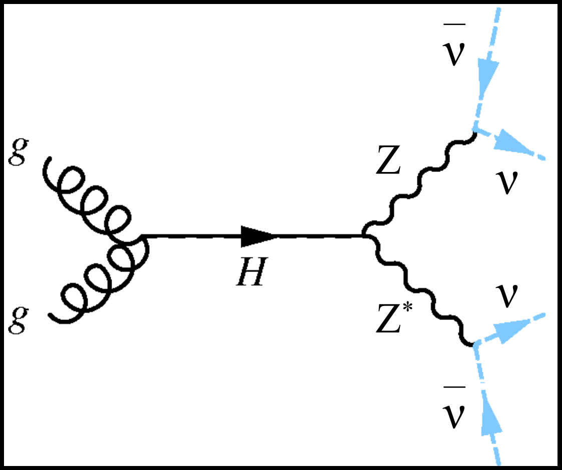
JHEP 10 (2017) 112

Combined obs (exp) UL on σ×B(H→ℓℓγ)
3.9 (2.9) × SM

Observed (expected) UL on σ×B(H→Zγ)
6.6 (5.2) × SM

INVISIBLE HIGGS

Higgs Decay to invisible

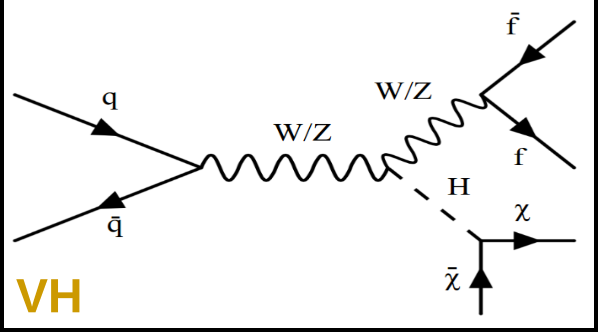


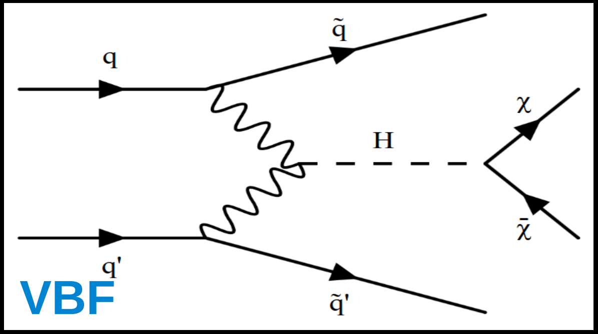
- In SM only possible via Higgs decay to Z bosons

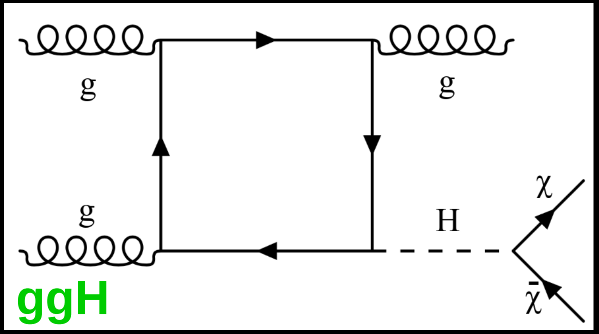
$$B(H \rightarrow ZZ \rightarrow Inv.) \leq 10^{-4}$$

- Current limits leave room for possible BSM effects in Higgs decay to invisible

- All Higgs production mechanisms can be exploited!







Higgs decay to invisible

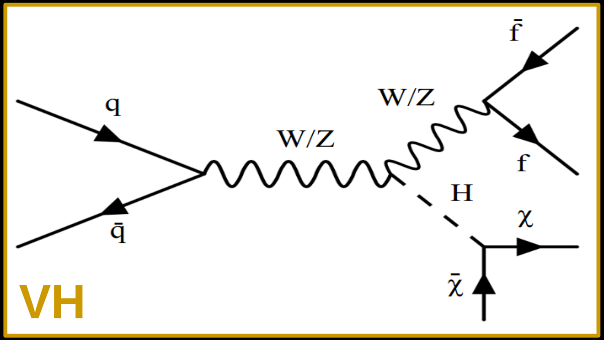
Two different signatures with large E_T^{miss}:

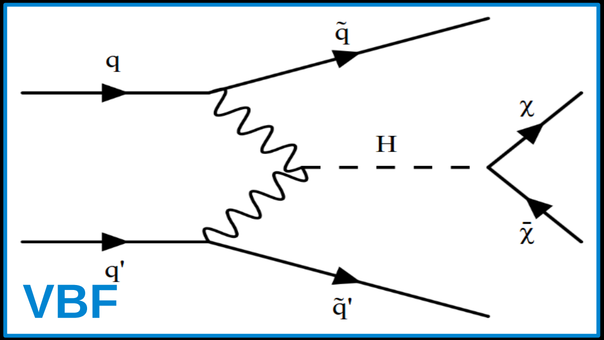
- $Z \rightarrow \ell\ell$
- Boosted $V \rightarrow qq'$

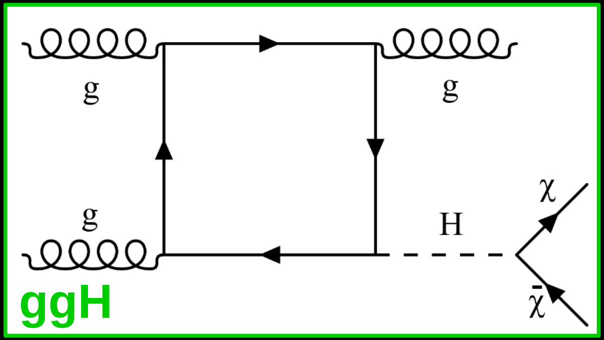
Large E_T^{miss} and 2 VBF jets

Monojet analysis with large E_T^{miss}

- No overlap with VH or VBF







Eur. Phys. J. C 78 (2018) 291

Phys. Rev. D 97, 092005 (2018)

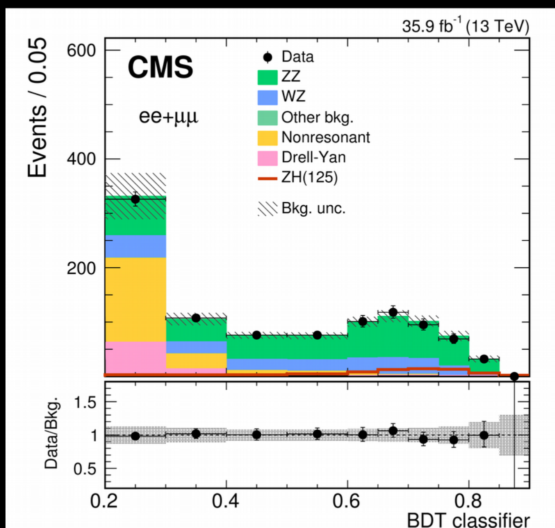
Phys. Lett. B 776 (2017) 318

CMS-HIG-17-023

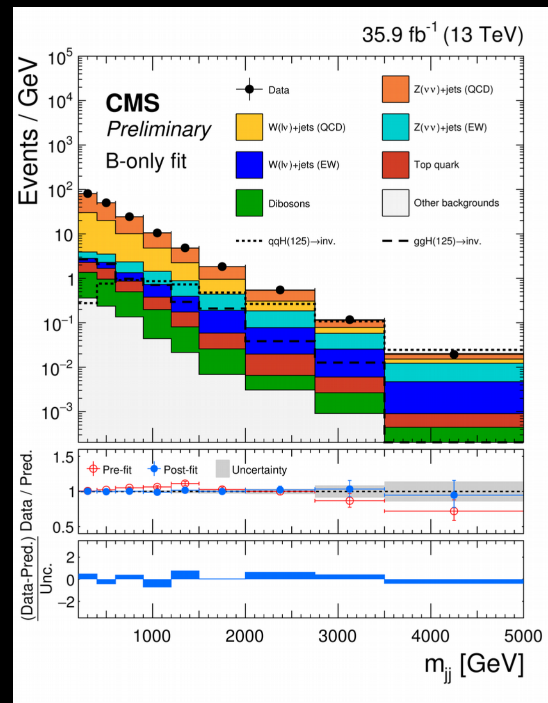
Phys. Rev. D 97, 092005 (2018)

Higgs decay to invisible

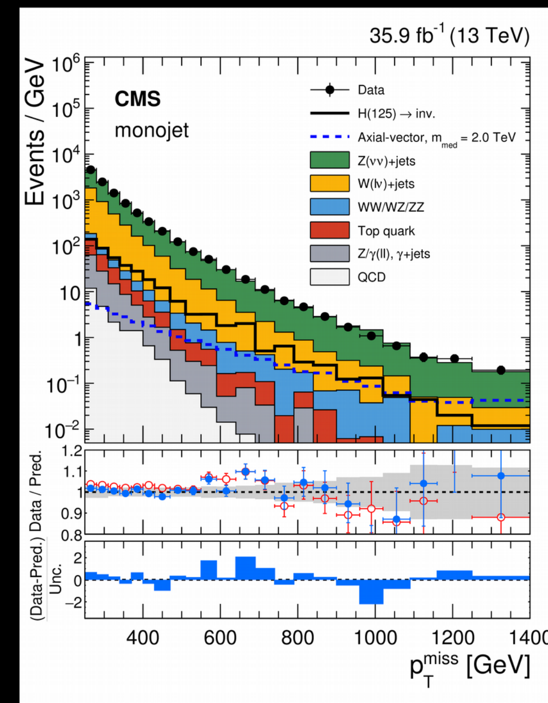
$Z \to \ell\ell$: fit to BDT against WZ/ZZ



Fit to m_{jj} distribution



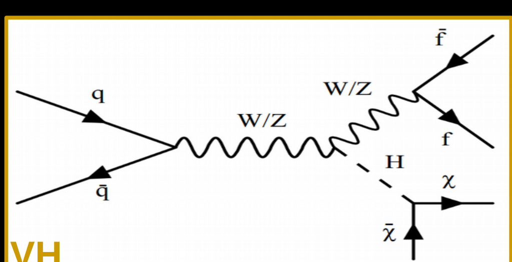
Fit to E_T^{miss}

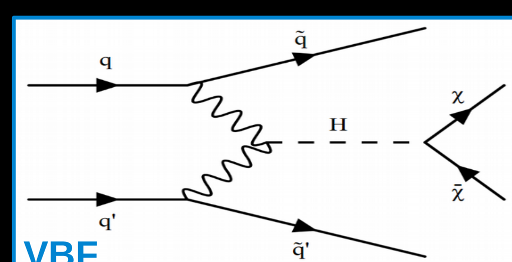


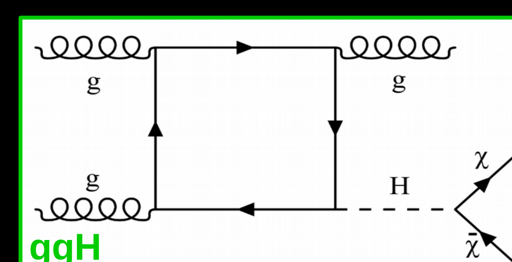
Major backgrounds from data

Major backgrounds from data

Major backgrounds from data







Results and combination

CMS-HIG-17-023

Observed (expected) upper limits at 95% CL:

VH

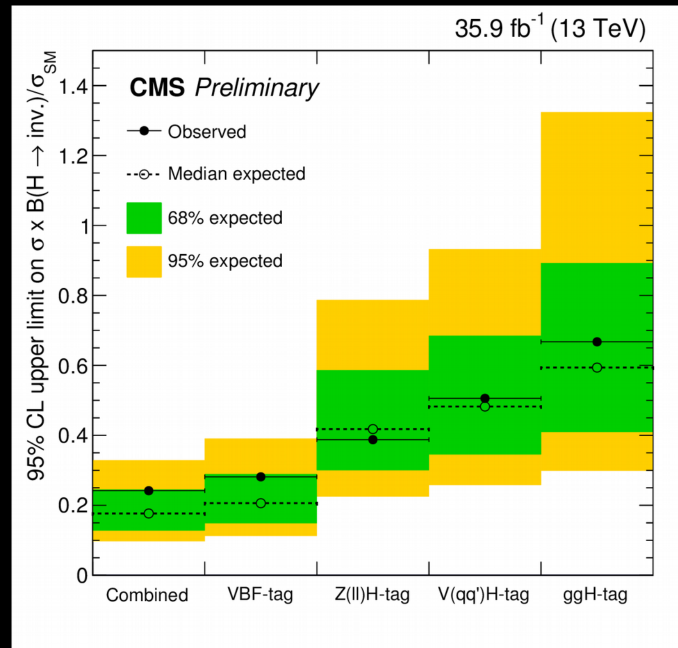
Z(ℓℓ): B(H→ inv) < 40 (42)%
Z(qq'): B(H→ inv) < 50 (48)%

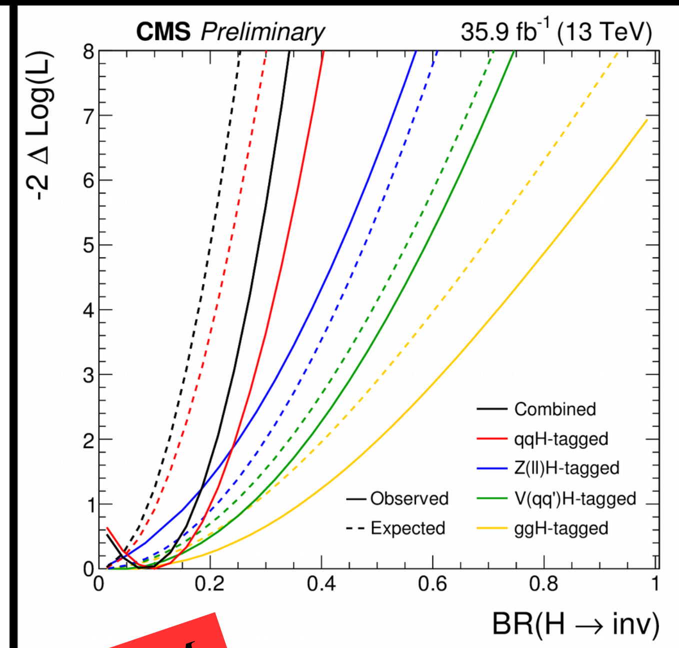
VBF

B(H→ inv) < 28 (21) %

ggH

B(H→ inv) < 66 (59)%





σ_H from SM

Combined observed (expected) limit from all channels at 95% CL

B(H→ inv) < 24 (18) %

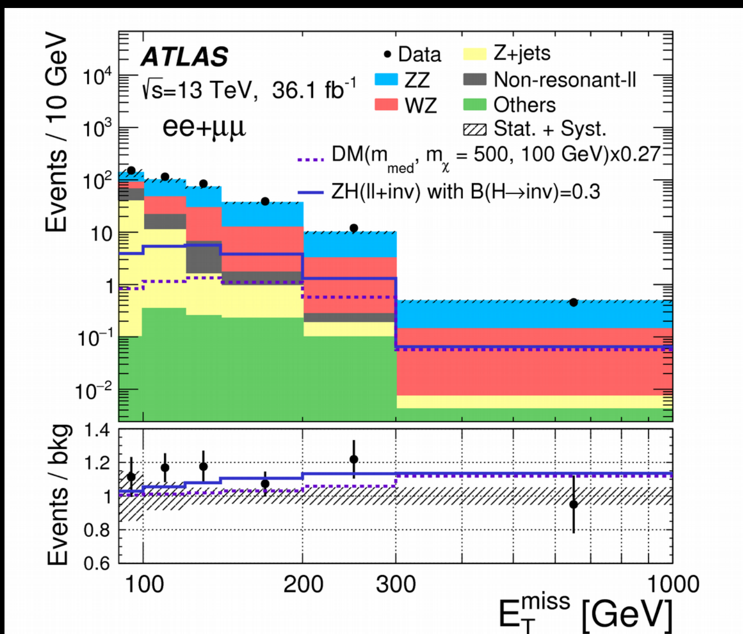
- Competitive with the results of Higgs coupling measurements
- Still much larger than the SM prediction!

Higgs decay to invisible

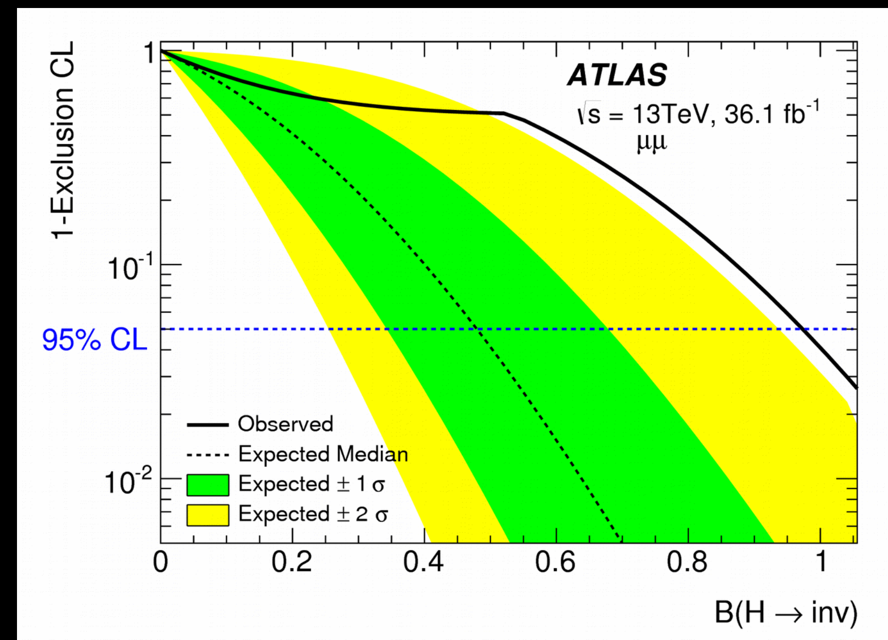
Phys. Lett. B 776 (2017) 318

Similar search from ATLAS in VH

Fit to E_T^{miss} distribution

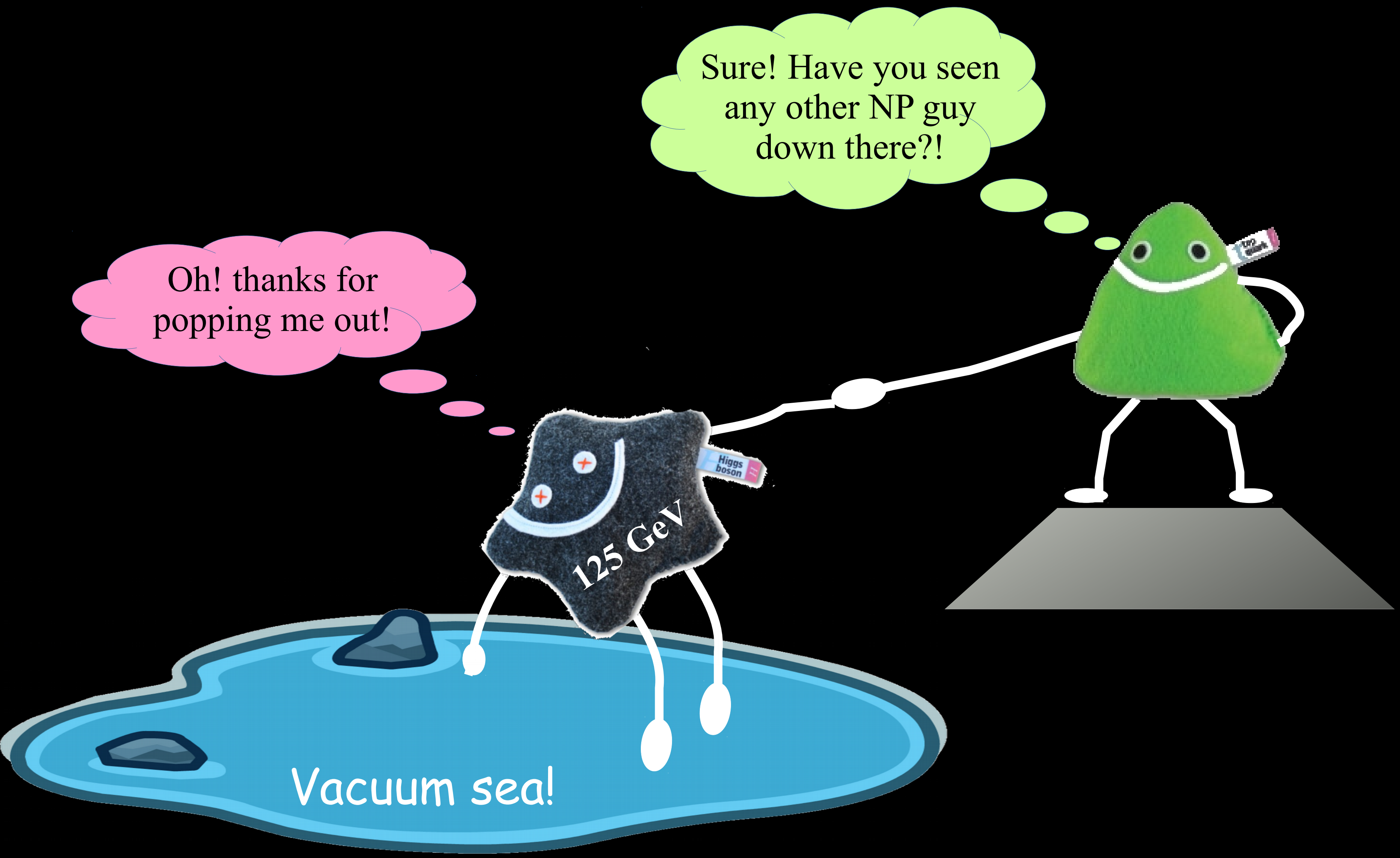


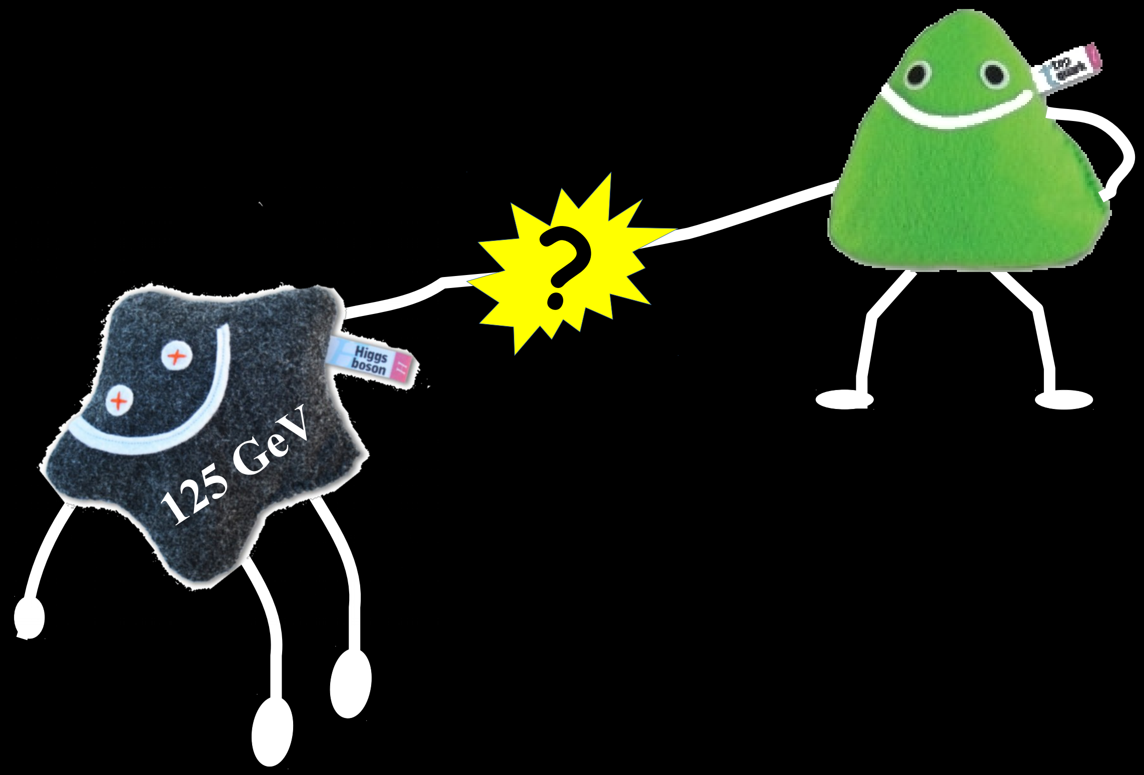
Mild excess in μμ channel



	Obs. $B_{H\to\text{inv}}$ Limit	Exp. $B_{H\to\text{inv}}$ Limit $\pm1\sigma\pm2\sigma$
ee	59%	$(51\ ^{+21}_{-15}\ ^{+49}_{-24})$ %
$\mu\mu$	97%	$(48\ ^{+20}_{-14}\ ^{+46}_{-22})$ %
$ee+\mu\mu$	67%	$(39\ ^{+17}_{-11}\ ^{+38}_{-18})$ %

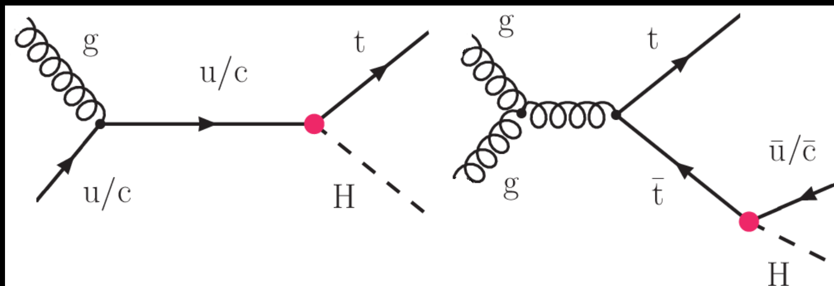
Combined limit at 95% CL
B(H→inv) < 67%

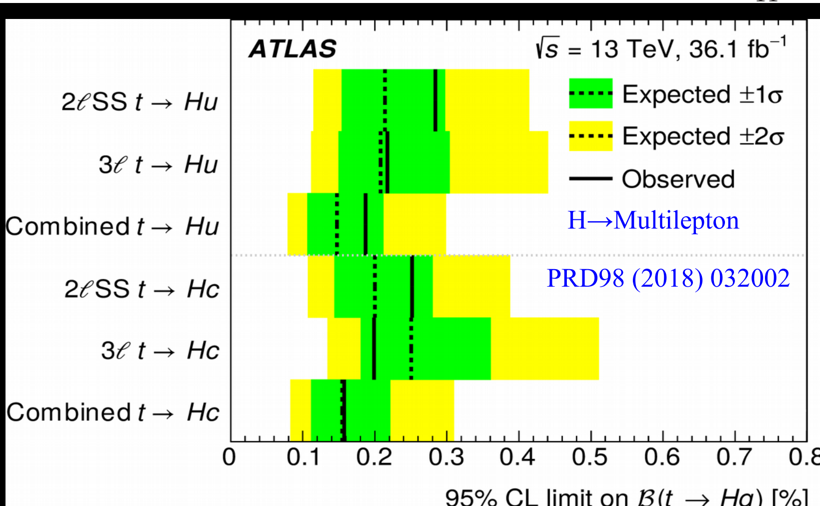

Sure! Have you seen any other NP guy down there?!
Oh! thanks for popping me out!
Higgs boson
125 GeV
Vacuum sea!

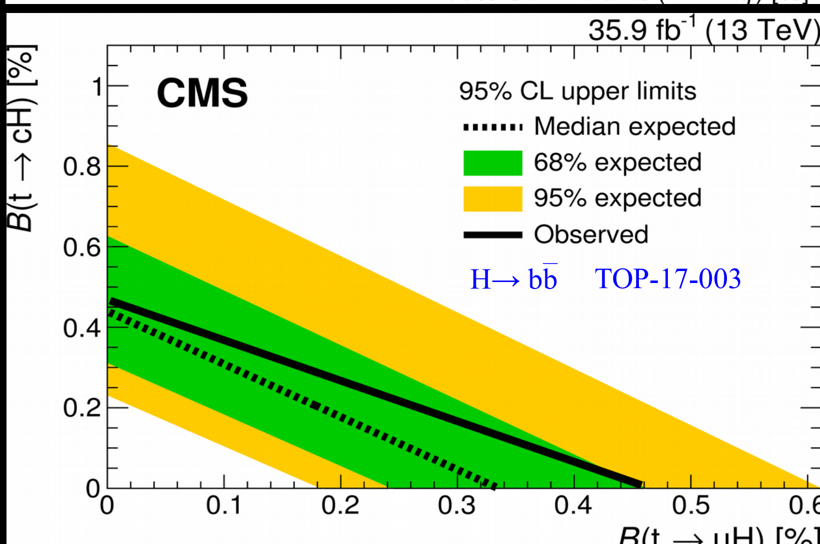


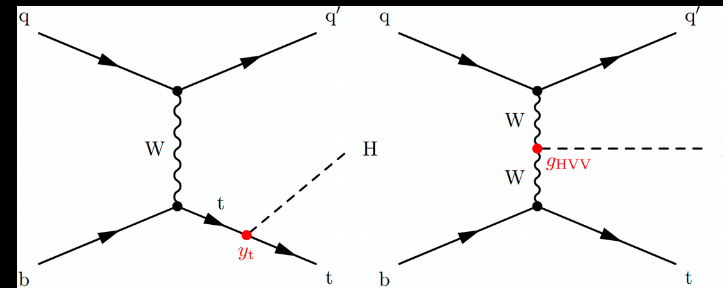
HIGGS ANOMALOUS INTERACTIONS

FCNC and inverted top-H coupling

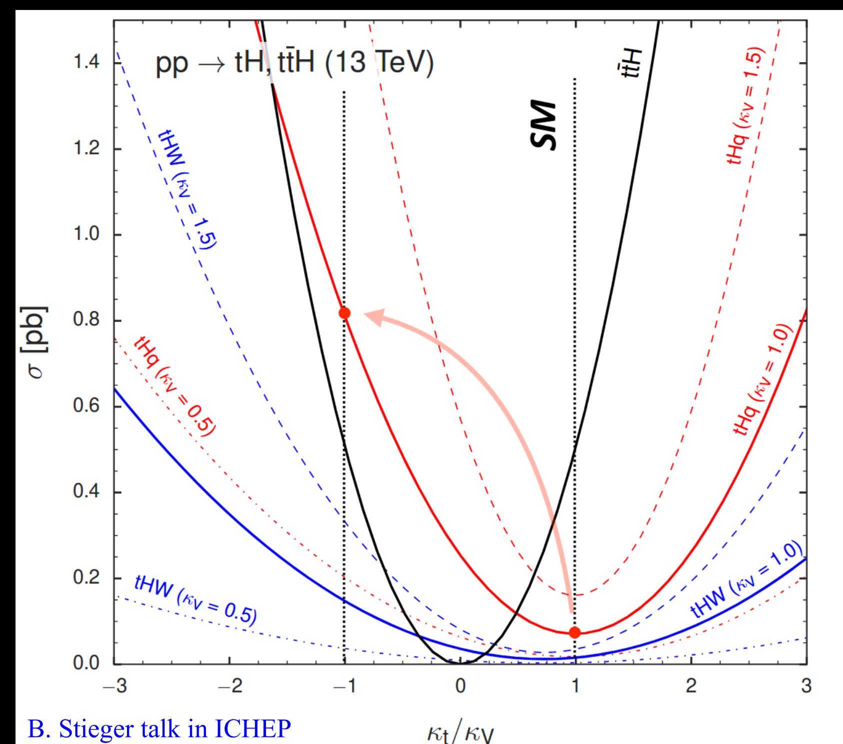








$\boldsymbol{\sigma_{tHq}}$ sensitive to amplitude, relative sign & phase of y_t and g_{HVV}.



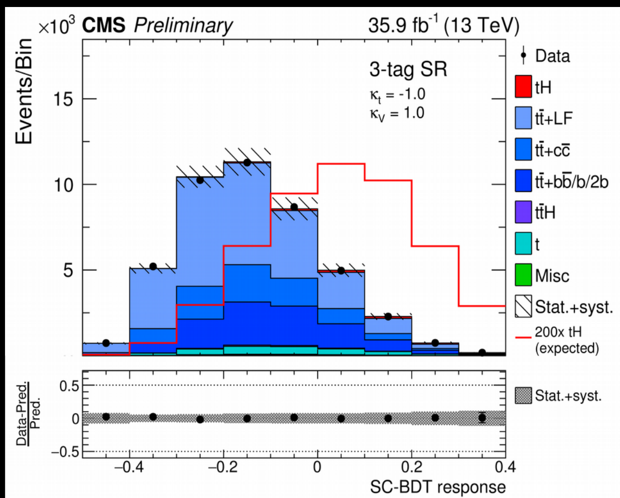
κ: ratio of the coupling to SM

Inverted top-H coupling: tHq search

CMS-HIG-18-009

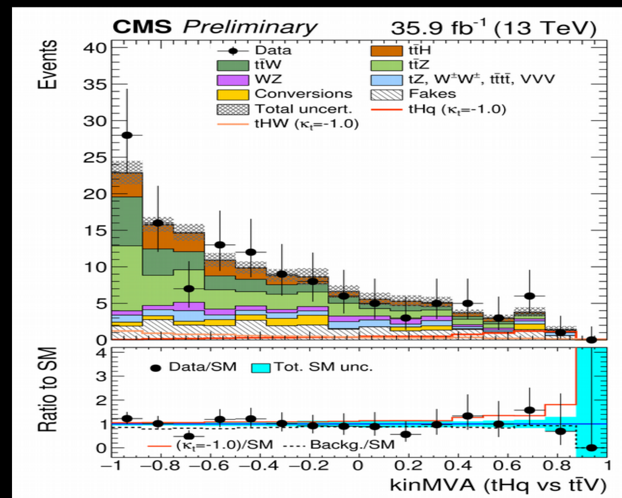
Three analysis are combined

H→ $b\bar{b}$ (HIG-17-016)



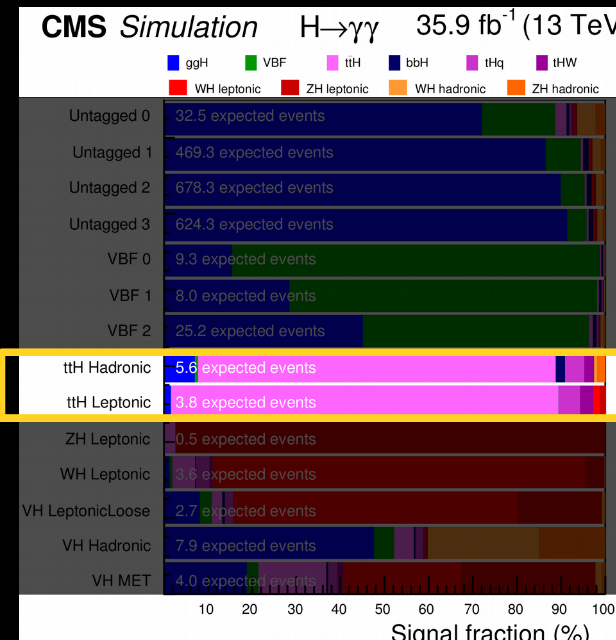
- Dedicated analysis
  - Signal: $\kappa_t = -1$
  - Simultaneous fit to BDT in various regions

Multi-lepton H→ WW/ZZ/ττ (HIG-17-005)



- Dedicated analysis
  - Signal: $\kappa_t = -1$
  - Two BDT's merged ($t\bar{t}V$,$t\bar{t}$)
  - Fit to merged BDT

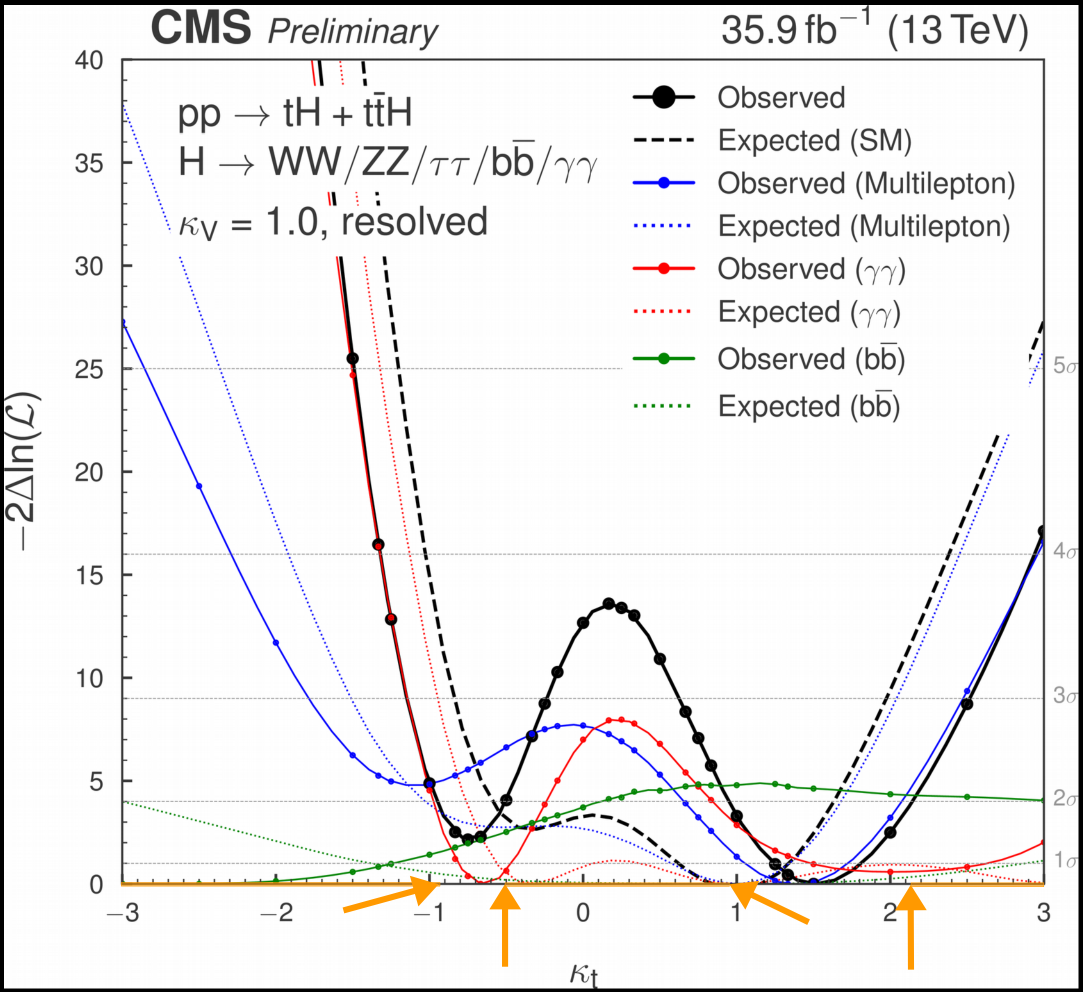
H→ γγ (arXiv:1804.02716)



- $t\bar{t}H$ categories from H→ γγ measurement
- Signal efficiency and acceptance evaluated for $\kappa_t = -1$

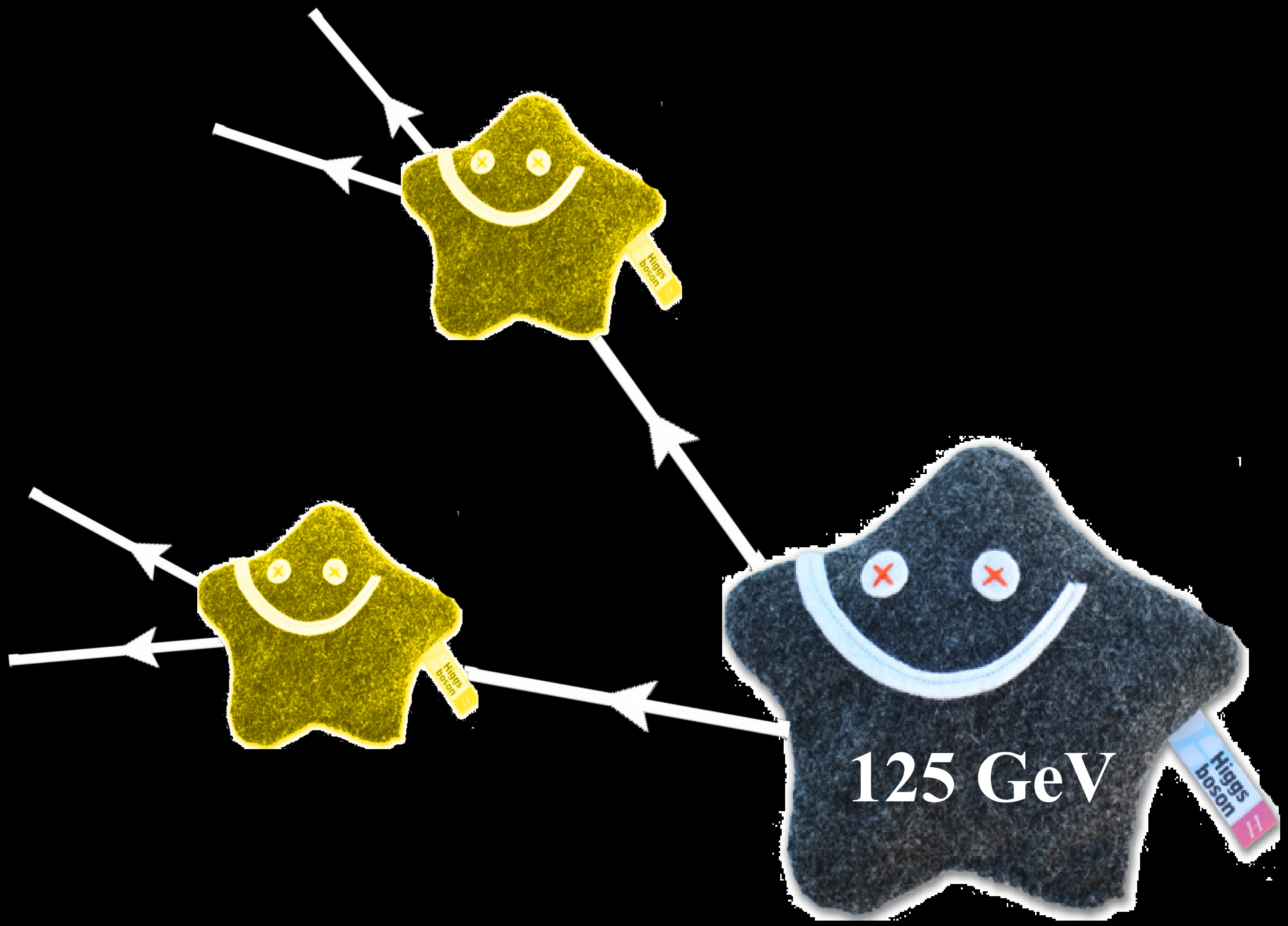
Inverted top-H coupling: tHq search

CMS-HIG-18-009

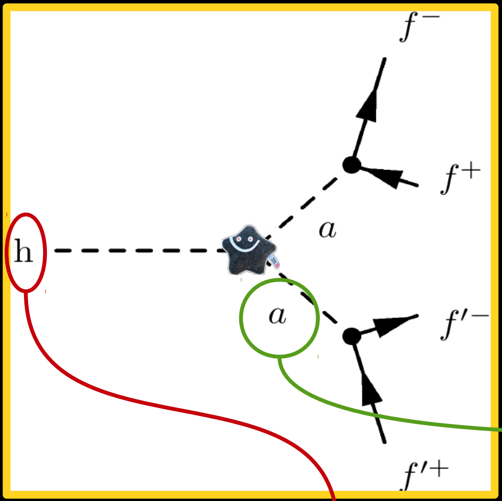


Inverted coupling is not entirely excluded!

- Data constrain y_t to within [-0.9, -0.5] and [1.0, 2.1] times y_t^{SM}
- Slightly favor positive sign of y_t at about 1.5 σ



HIGGS EXOTIC DECAYS

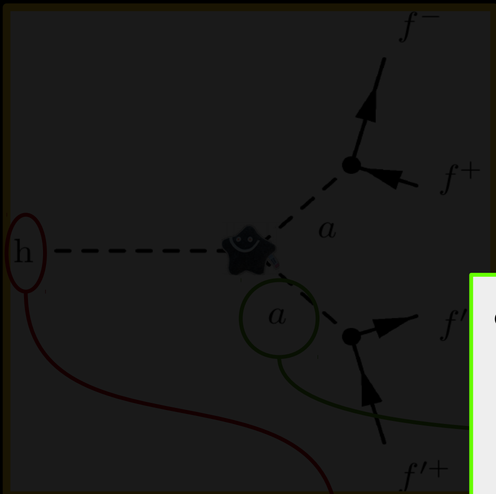


- Well motivated in the framework of NMSSM, 2HDM+S, …
- Handful of analyses in LHC Run I!
- Also plenty of results at 13 TeV

A pseudoscalar, interacts with fermions via mixing with Higgs

One of the light CP-even Higgs in the model identified as h(125)

Explored final states at LHC 13 TeV		
$H\rightarrow aa\rightarrow 4\ell$	ATLAS EXPERIMENT JHEP 06 (2018) 166,	CMS CMS-HIG-18-003, arXiv:1805.04865 (Acc. JHEP)
$H\rightarrow aa\rightarrow bb\ell\ell$	ATLAS EXPERIMENT arXiv:1807.00539,	CMS arXiv:1805.10191 (Acc. PLB)
$H\rightarrow aa\rightarrow 4b$	ATLAS EXPERIMENT arXiv:1806.07355	
$H\rightarrow aa\rightarrow gg\gamma\gamma$	ATLAS EXPERIMENT PLB 782 (2018) 750	



One of the light CP-eve… in the model identified as h(125)

- Well motivated in the framework of NMSSM, 2HDM+S, …
- Handful of analyses in LHC Run I!

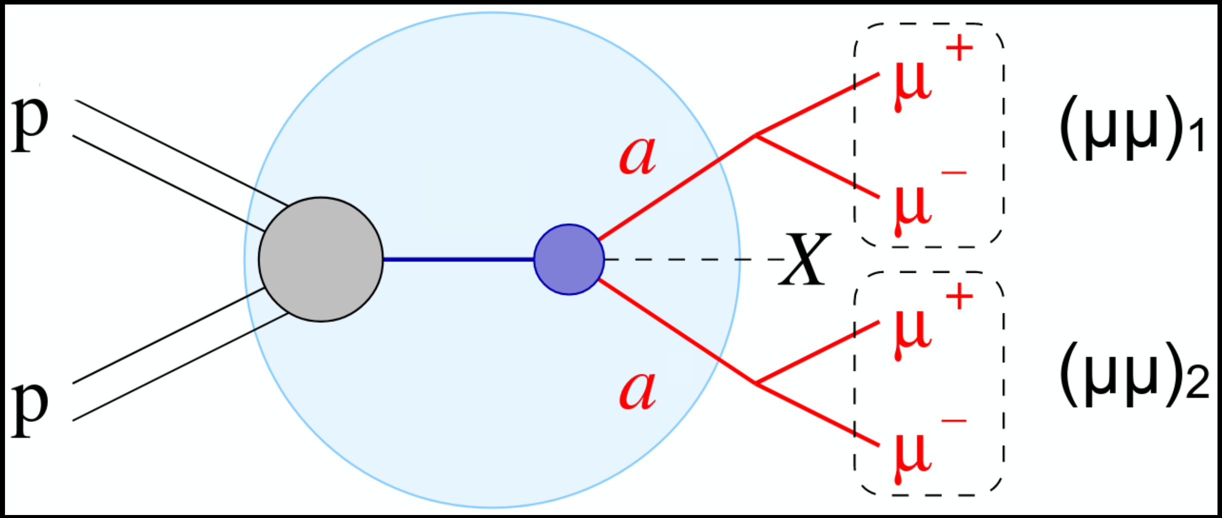
… via mixing with Higgs

- Some specific features
  - b-jets with a possibility to merge …
  - Hadronically decaying τ leptons
  - Decays to gauge bosons
  - Lower mass ranges for the *a* boson

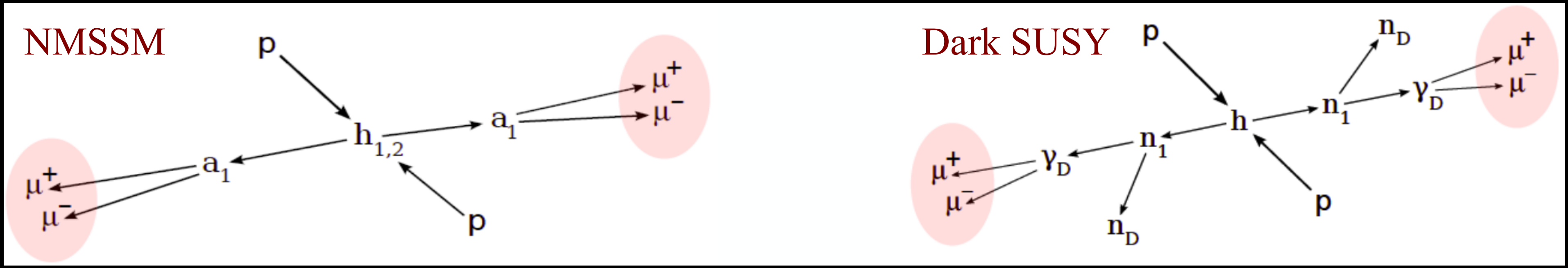
Explored final states at LHC 13 TeV		
H→*aa*→4ℓ	ATLAS: JHEP 06 (2018) 166,	CMS: **CMS-HIG-18-003**, arXiv:1805.04865 (Acc JHEP)
H→*aa*→bbℓℓ	ATLAS: arXiv:1807.00539,	CMS: **arXiv:1805.10191** (Acc. PLB)
H→*aa*→4b	ATLAS: **arXiv:1806.07355**	
H→*aa*→ggγγ	ATLAS: **PLB 782 (2018) 750**	

CMS-HIG-18-003

- Model-independent search in mass range of 0.25 – 8.5 GeV
- Only rely on muon pairing!



- Benchmark models: NMSSM & Dark SUSY

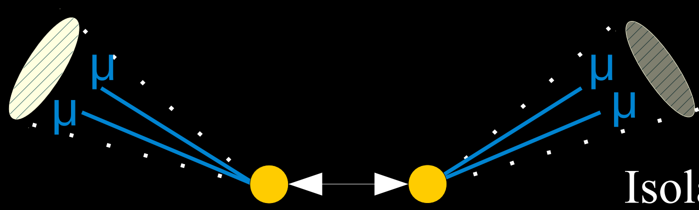


90 GeV < $m(h_{1,2})$ < 150 GeV
0.25 GeV < m(a1) < 3.55 GeV

0.25 < $m(\gamma_D)$ < 8.5 GeV
m_{n1} = 10 GeV, m_{nD} = 1 GeV,
0 mm < $c\tau(\gamma_D)$ < 100 mm

CMS-HIG-18-003

Dedicated muon pairing

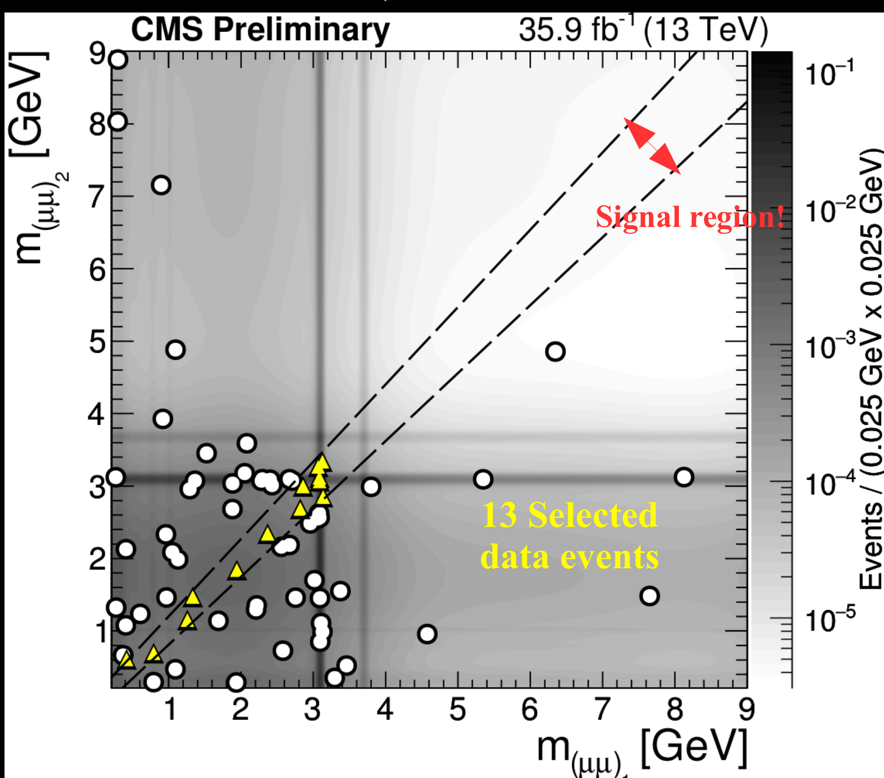


Isolated pairs

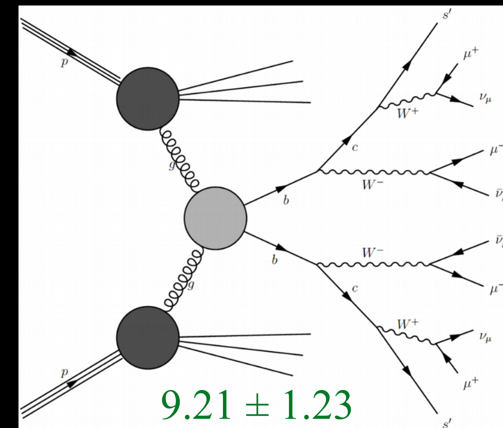
Same origins for *a*'s

$m_{\mu\mu 1} = m_{\mu\mu 2}$

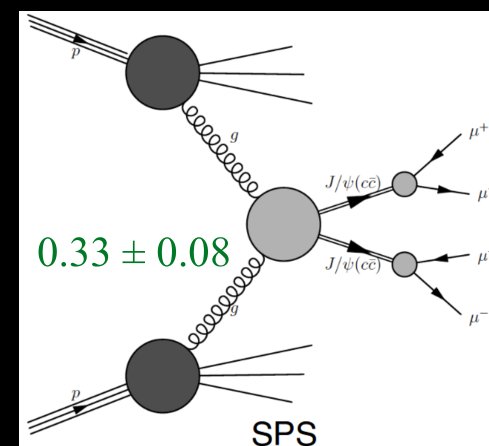
m_a-dependent resolution



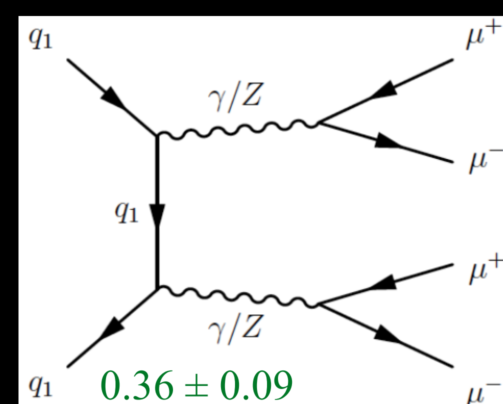
Backgrounds



From data

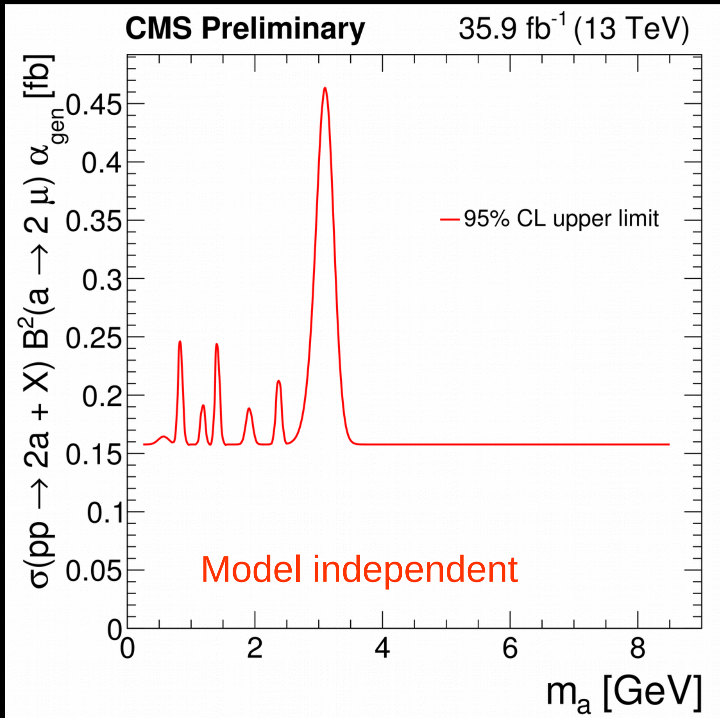


From data

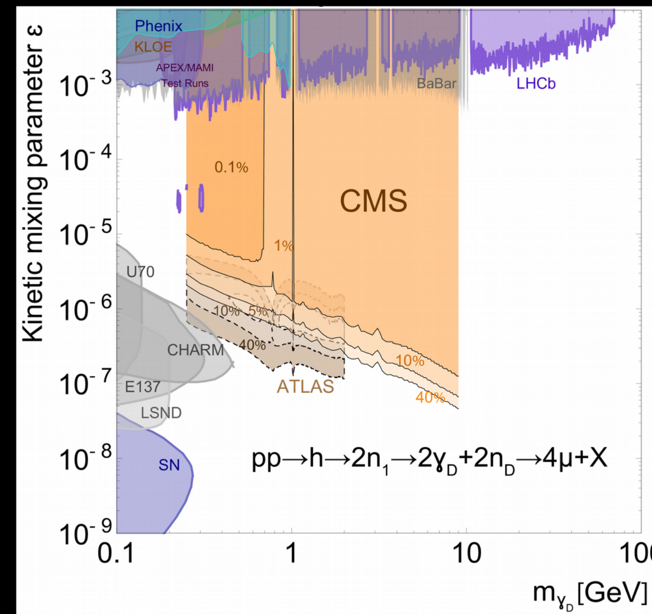


From MC

CMS-HIG-18-003

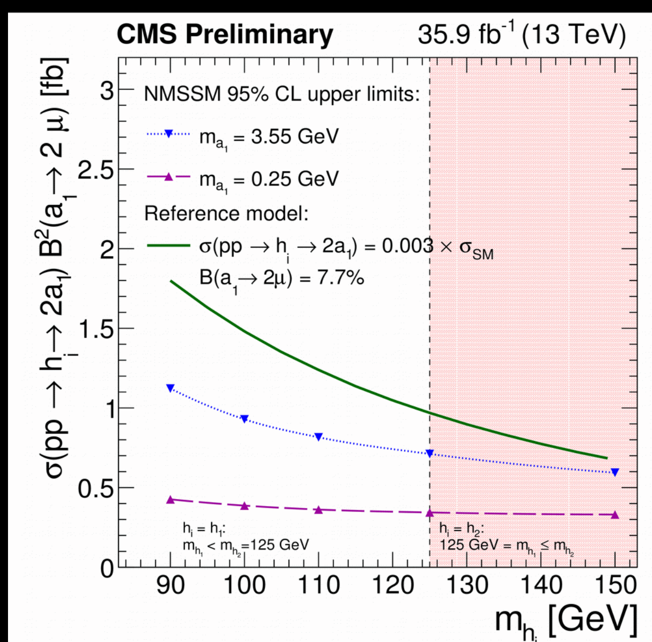


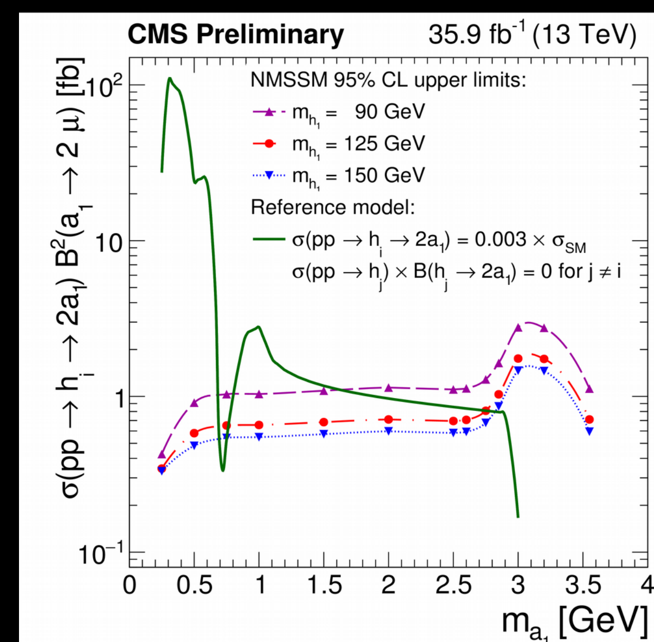
Dark SUSY



NMSSM

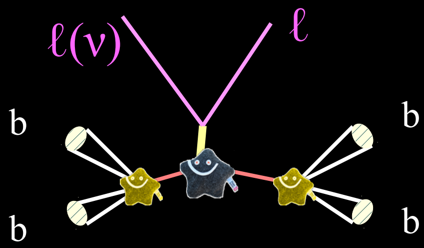
NMSSM



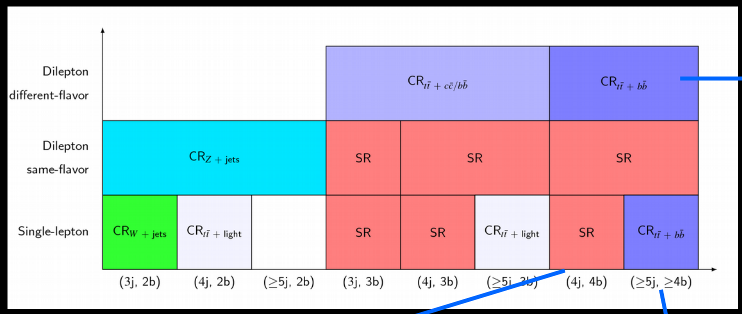


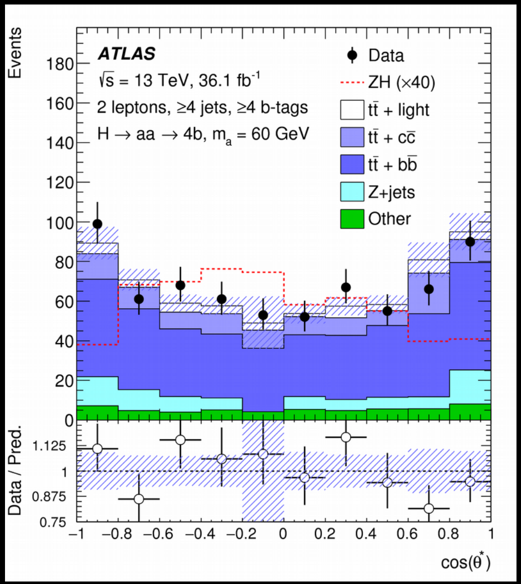
H→*aa*→4b (VH)

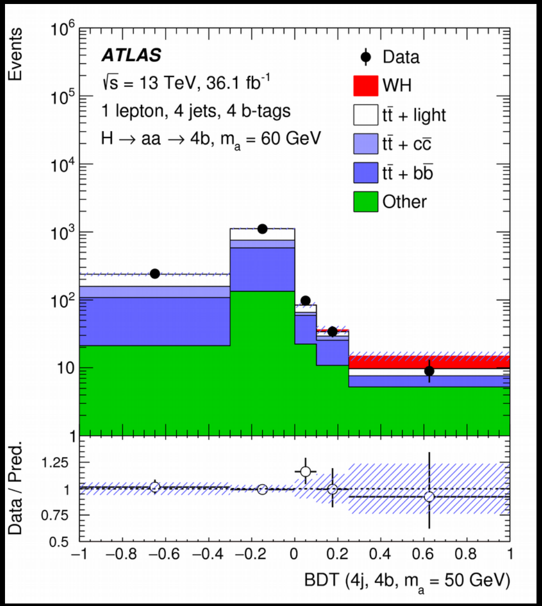
arXiv:1807.00802

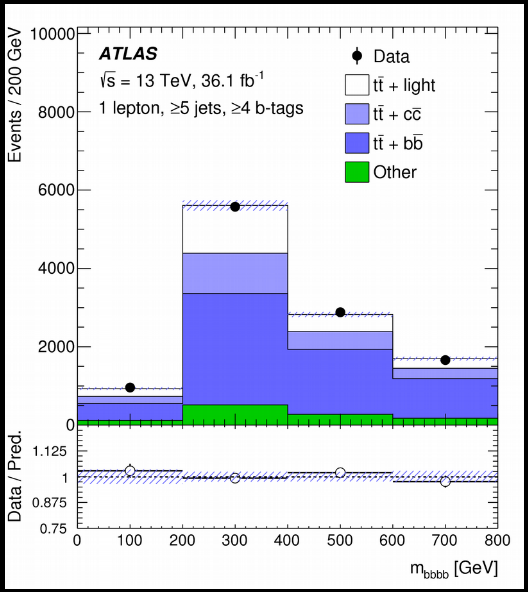


- Categories in number of leptons, jets and b-jets
- BDT trained in SR, other discriminative variables in CR
- Simultaneous fit of all regions



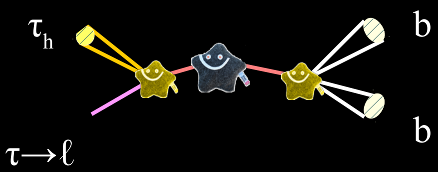






$H \to aa \to \tau\tau bb$ (all)

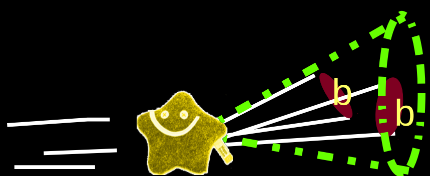
arXiv:1805.10191



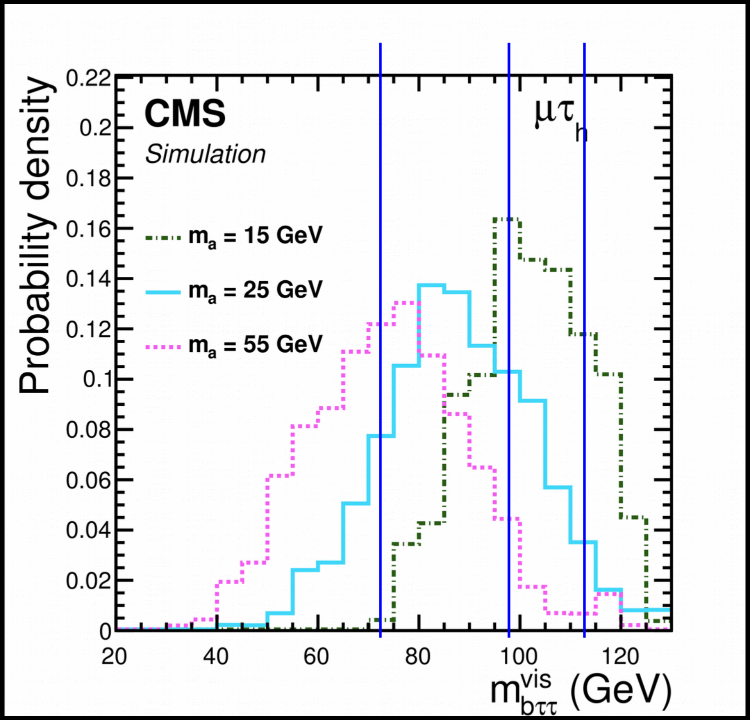
- The final states of $\tau_h\tau_\ell$ and $\tau_e\tau_\mu$ are considered
- Categorization based on $m_{b\tau\tau}$, threshold depends on the final state

E_T^{miss}-based topological cuts

Boosted a at low m_a



Merged b-jets, Larger $m_{b\tau\tau}$

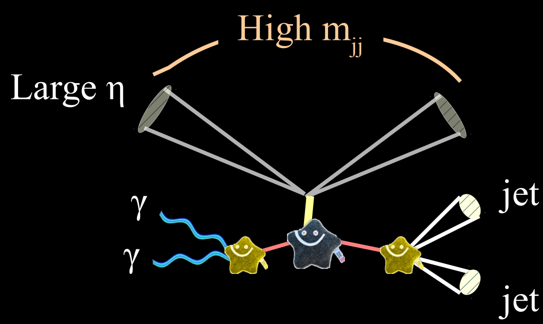


Simultaneous fit to $m_{b\tau\tau}$ in all categories

$H \to aa \to \gamma\gamma jj$ (VBF)

ATLAS EXPERIMENT

PLB 782 (2018) 750



Four-body mass compatible with m_H

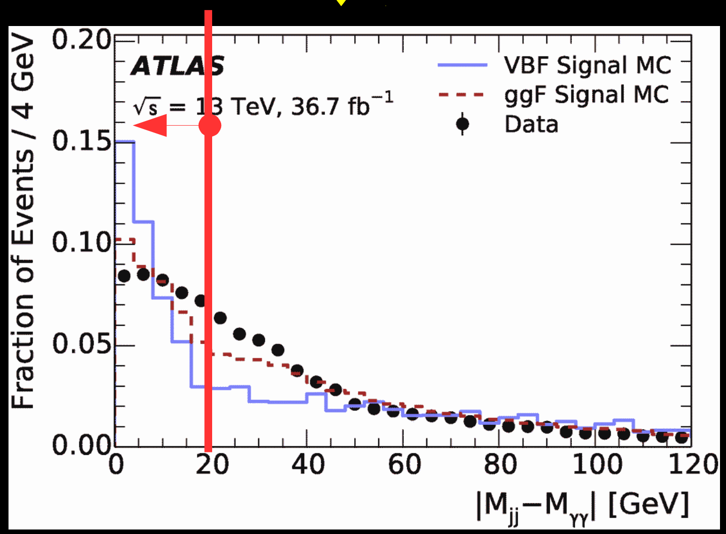
100 GeV < $m_{jj\gamma\gamma}$ < 150 GeV

Same origins for a's

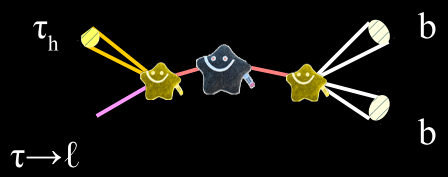
$m_{\gamma\gamma} = m_{jj}$

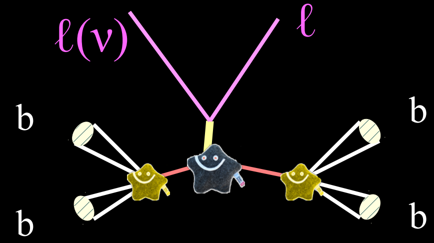
m_a-dependent resolution

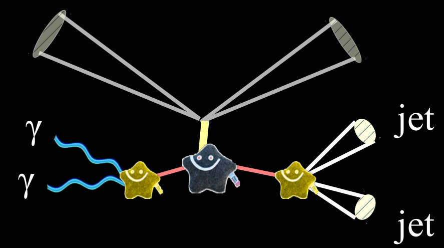
m_a-dependent cut

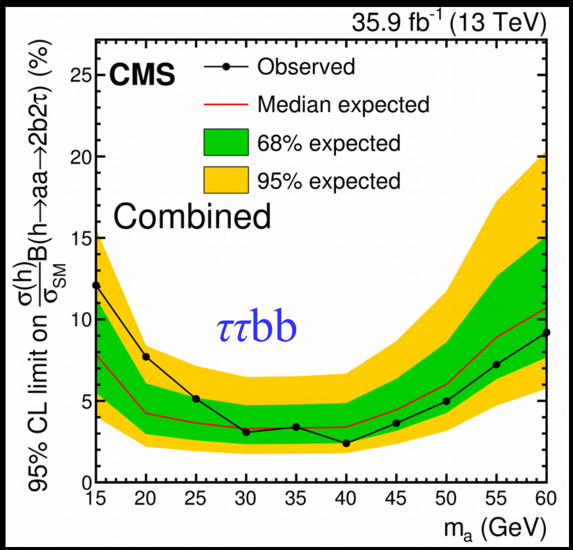


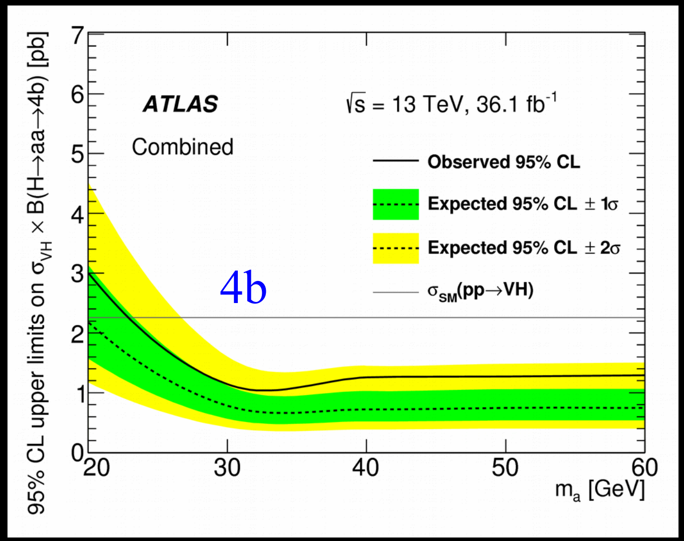
H→*aa* with m_a > 20 GeV

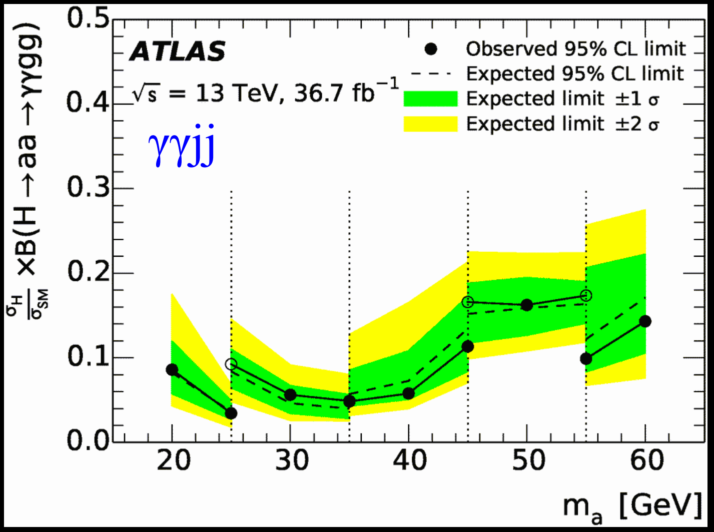












2% < B(H→BSM) < 8%

Sensitivity degrades in m_a < 20 GeV

Best B(H→BSM) < 45%

4% < B(H→BSM) < 16%

Summary

LHC Higgs measurements has entered the precision era!

- ➔ Many Higgs properties are measured and challenging Higgs processes are discovered
- ➔ Small deviations from SM might be probed in Higgs differential and properties measurements

Rare signatures might be the key for future discoveries

- ➔ Direct searches provide complementarity to capture new physics effects!

ATLAS and **CMS** have a rich program to exploit the BSM discovery potential of the Higgs boson

- ➔ Already a handful of results, no significant sign of BSM yet!

Stay tuned!

BACKUP

H→ bb

- VH: W→ℓυ, Z→ ℓℓ/υυ
- Dedicated b-jet energy calibration

Table 1: Summary of the event selection and categorisation in the 0-, 1- and 2-lepton channels.

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 *loose* leptons with $p_T > 7$ GeV	1 *tight* electron $p_T > 27$ GeV	1 *tight* muon $p_T > 25$ GeV	2 *loose* leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ GeV
E_T^{miss}	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_T	> 20 GeV for $\|\eta\| < 2.5$ and > 30 GeV for $2.5 < \|\eta\| < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_T	> 45 GeV			
H_T	> 120 (2 jets), >150 GeV (3 jets)	–		–
min[$\Delta\phi(E_T^{miss}, \textbf{jets})$]	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(E_T^{miss}, bb)$	$> 120°$	–		–
$\Delta\phi(b_1, b_2)$	$< 140°$	–		–
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			75 GeV $< p_T^V <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV yield		m_{bb} / yield Different-flavour leptons Opposite-sign charges

Two analysis:

1) BDT trained in SR's: ZH for signal extraction, ZZ for validation
2) Dijet mass analysis, using add. sel.

Selection	Channel: 0-lepton	1-lepton	2-lepton
m_T^W	-	< 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$
	p_T^V regions		
p_T^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	> 200 GeV
$\Delta R(b_1, b_2)$	<3.0	<1.8	<1.2

- Backgrounds from the fit in all categories
  - ℓυ: QCD bkg. from data using m_T^W fit (< 3% of total bkg).
- Dominant systematics: b-jet, jet and theory modeling
- Observed (expected) significance H→ bb:
  - This analysis: 4.9σ (4.3σ)
  - Combination with other production modes in Run I & Run II: 5.4σ (5.5σ)
- Observation of VH in Run II: 5.3σ (4.8σ)

H→ bb

- VH: W→ℓυ, Z→ ℓℓ/υυ
- Similar categorization to ATLAS with slightly different cuts and topological requirements
  → e.g. dedicated b-jet energy regression per lepton category (10–13% m_{jj} resolution)

- **Two analyses:**
  - Dijet mass
  - DNN (deep neural network)
    - Signal region: ZH for signal extraction, ZZ for validation
    - Control regions for tt (yield), Z+LF (yield), Z+HF (HFDNN, deepCSV in ℓℓ)

- Dominant systematics: b-jets, jets, theory modeling

VH only!

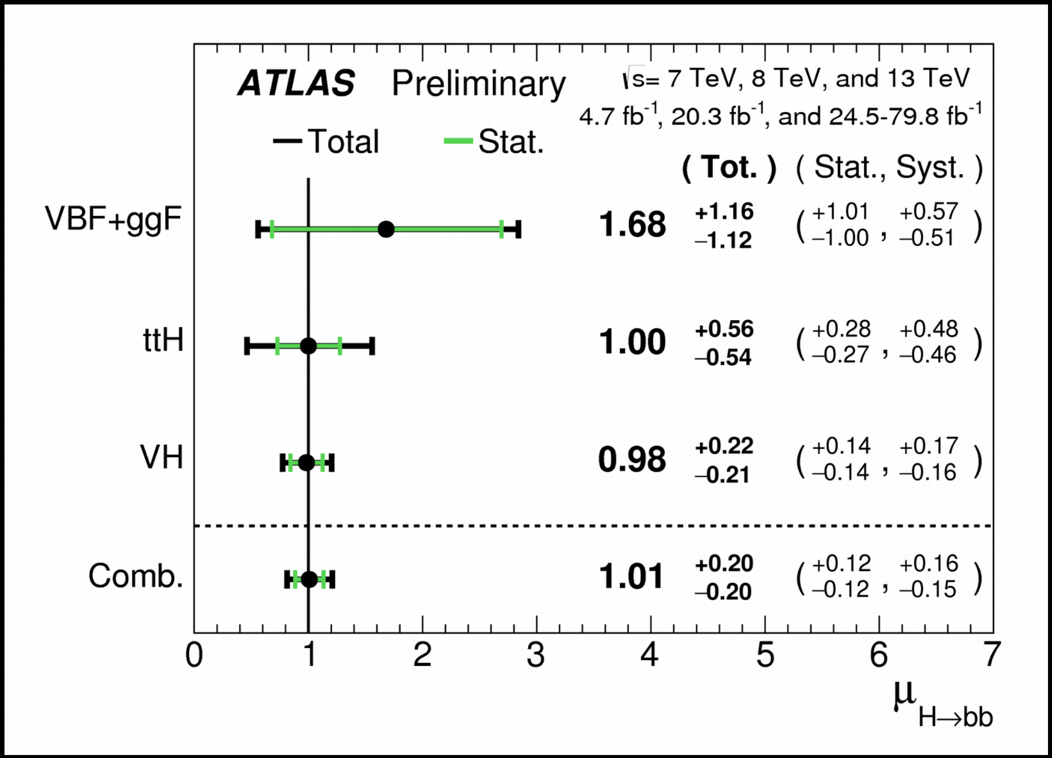
Channels	Significance Expected	Significance Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

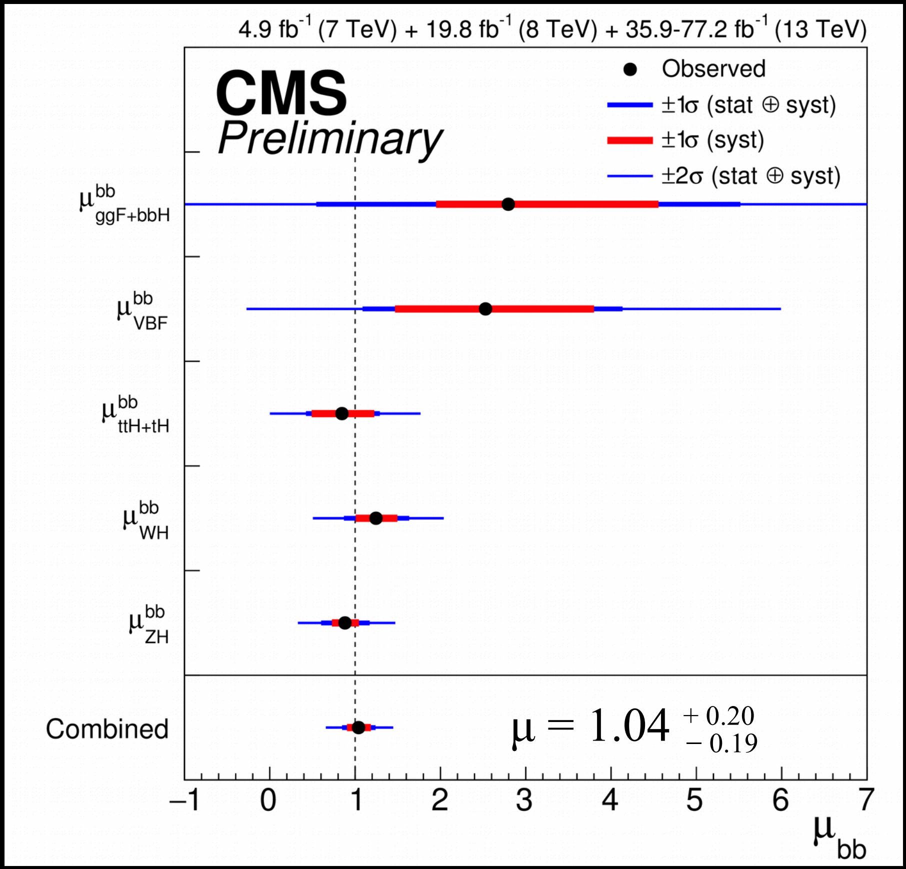
All production modes

Observed (expected) significance H→ bb

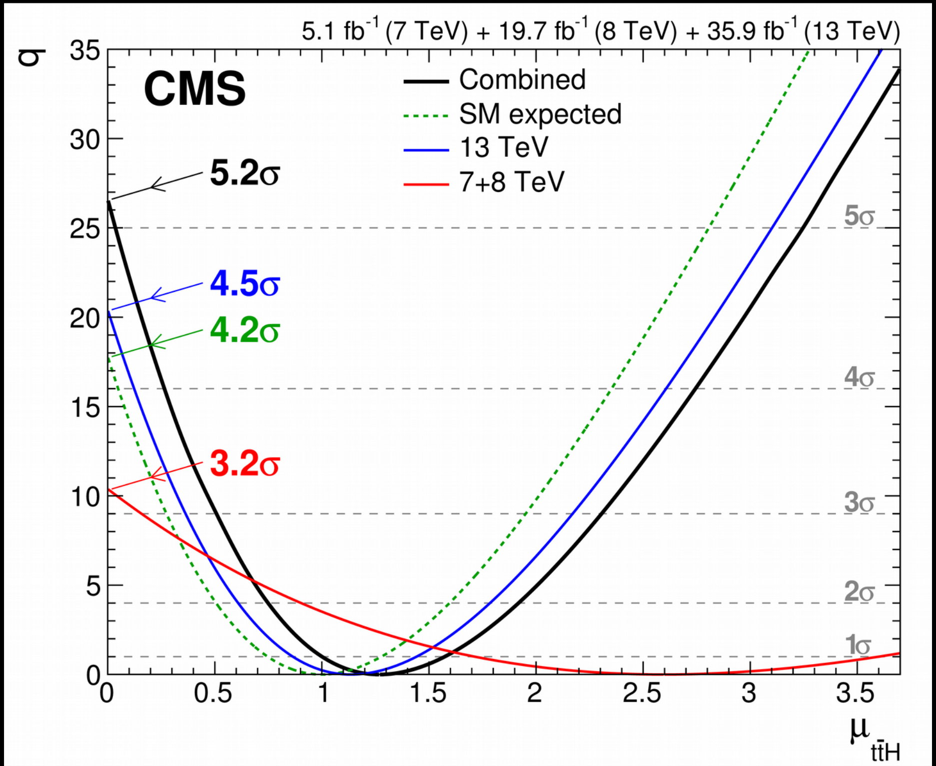
5.6σ (5.5σ)

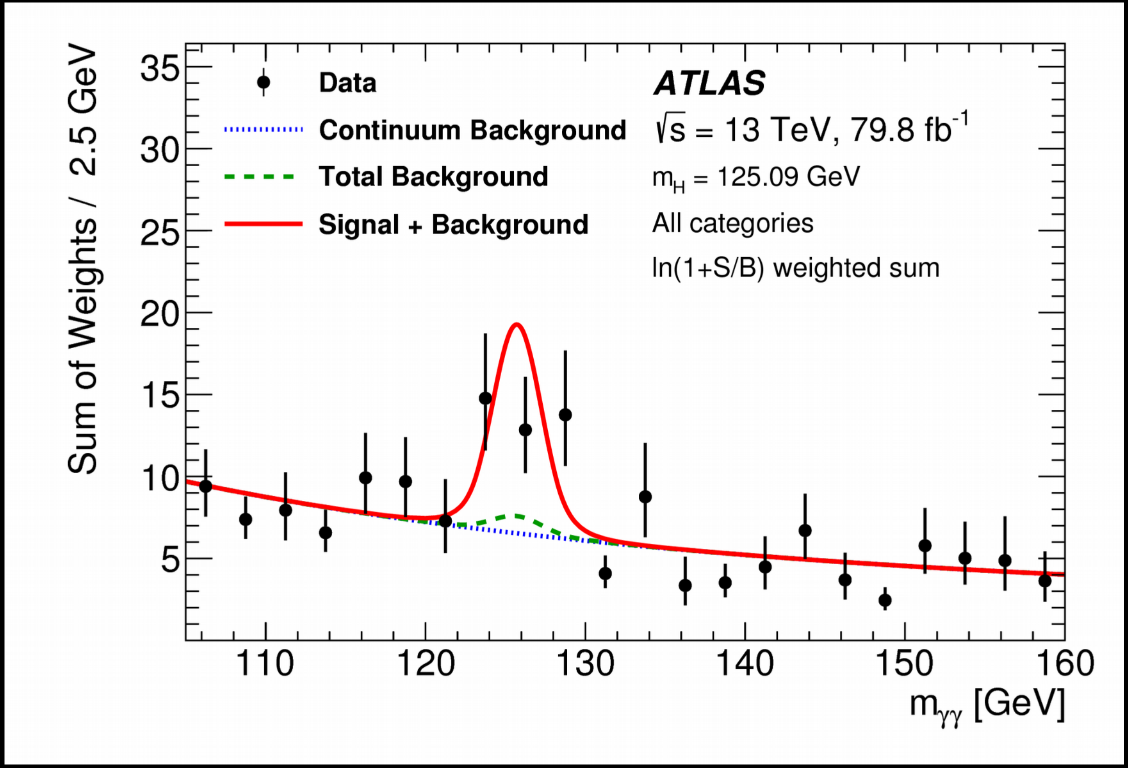
H→ bb


ATLAS Preliminary
√s= 7 TeV, 8 TeV, and 13 TeV
4.7 fb-1, 20.3 fb-1, and 24.5-79.8 fb-1
Total
Stat.
(Tot.) (Stat., Syst.)
VBF+ggF 1.68 +1.16 −1.12 (+1.01 −1.00 , +0.57 −0.51)
ttH 1.00 +0.56 −0.54 (+0.28 −0.27 , +0.48 −0.46)
VH 0.98 +0.22 −0.21 (+0.14 −0.14 , +0.17 −0.16)
Comb. 1.01 +0.20 −0.20 (+0.12 −0.12 , +0.16 −0.15)
0 1 2 3 4 5 6 7
μH→bb


4.9 fb-1 (7 TeV) + 19.8 fb-1 (8 TeV) + 35.9-77.2 fb-1 (13 TeV)
CMS
Preliminary
Observed
±1σ (stat ⊕ syst)
±1σ (syst)
±2σ (stat ⊕ syst)
μbb ggF+bbH
μbb VBF
μbb ttH+tH
μbb WH
μbb ZH
Combined
μ = 1.04 + 0.20 − 0.19
−1 0 1 2 3 4 5 6 7
μbb

ttH





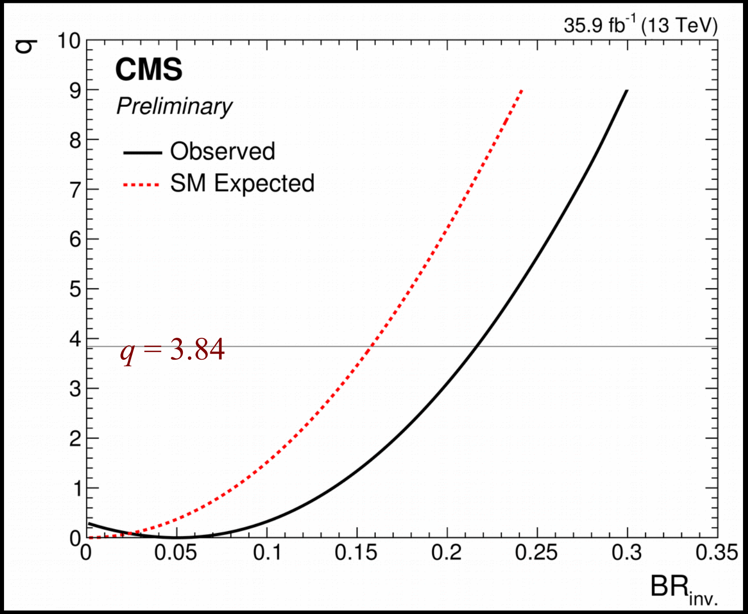
6.3σ (5.1σ) Observed (expected) significance combining channels in Run I + Run II

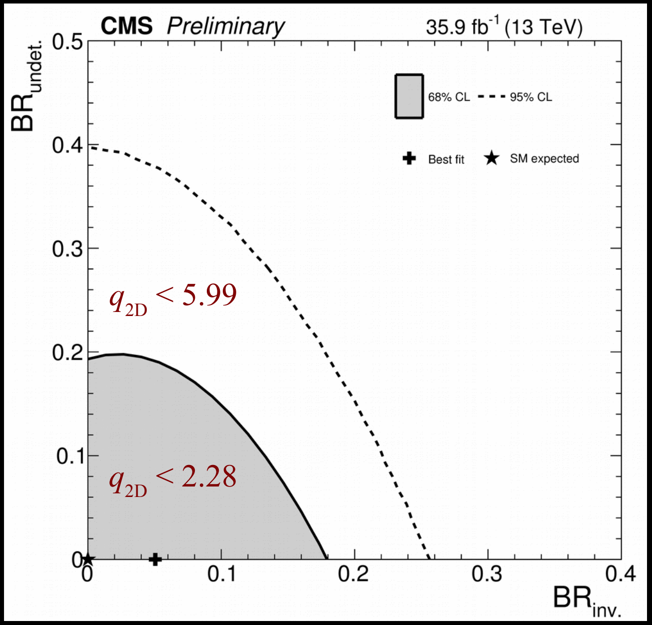
Combination

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

- Using κ framework for the coupling fit.
- B(H→BSM):
  - Invisible and undetected final states
    - ➔ Undetectable by ATLAS
    - ➔ Not covered by the analyses presented here
    - ➔ Modifications to the branching fractions of channels not yet been directly measured e.g., $H \to c\,\bar{c}$
- No BSM is assumed in "coupling-mass" fit

Combination



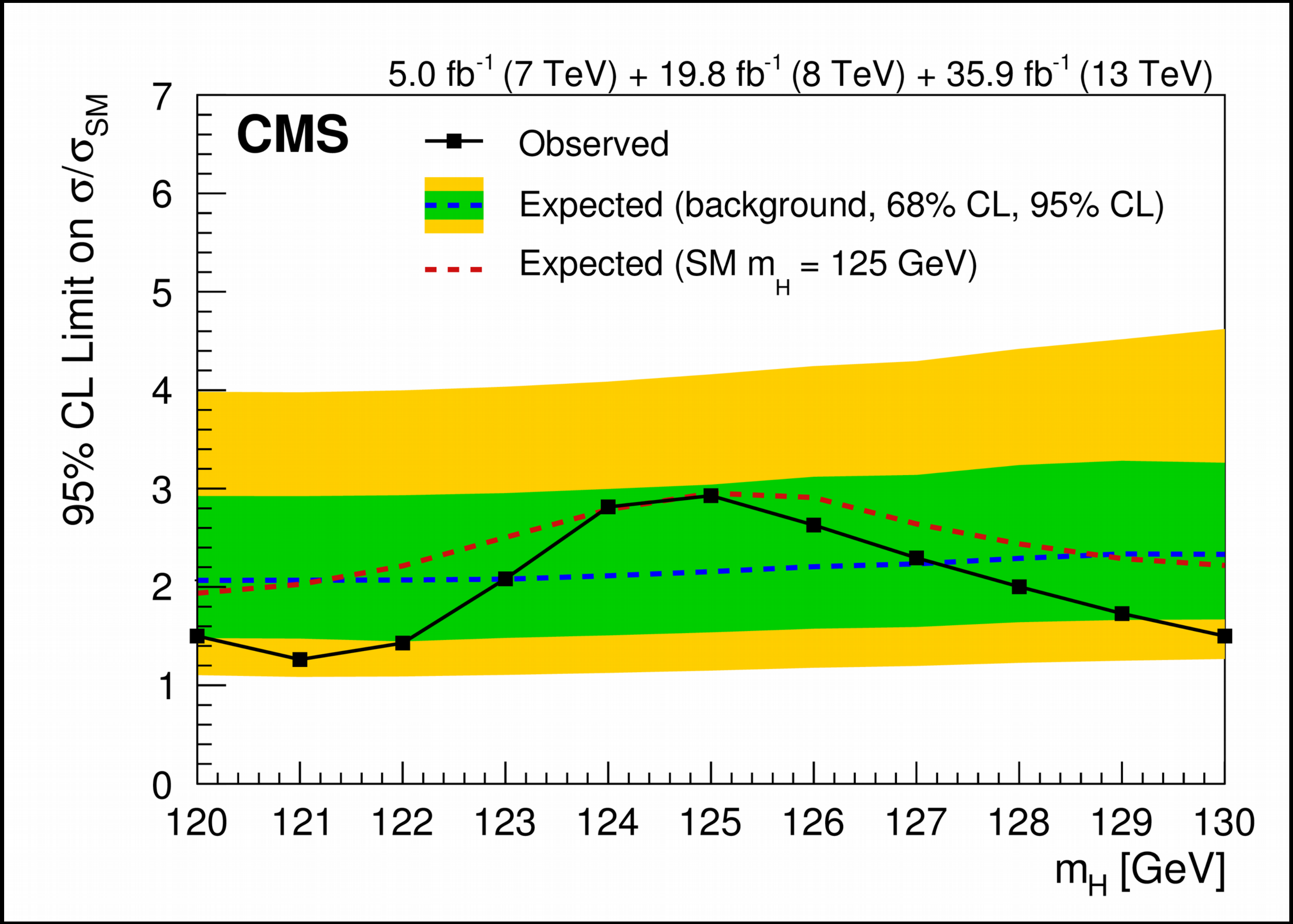


- Using κ framework for the coupling fit.
- B(H→BSM) ~ B(H→Inv.) & B(H→ Undet.):
  - $B_{undet.}$ represents the total branching ratio to any final state which is not detected by the channels included in this combined analysis.
- No BSM is assumed in “coupling-mass” fit

H→μμ

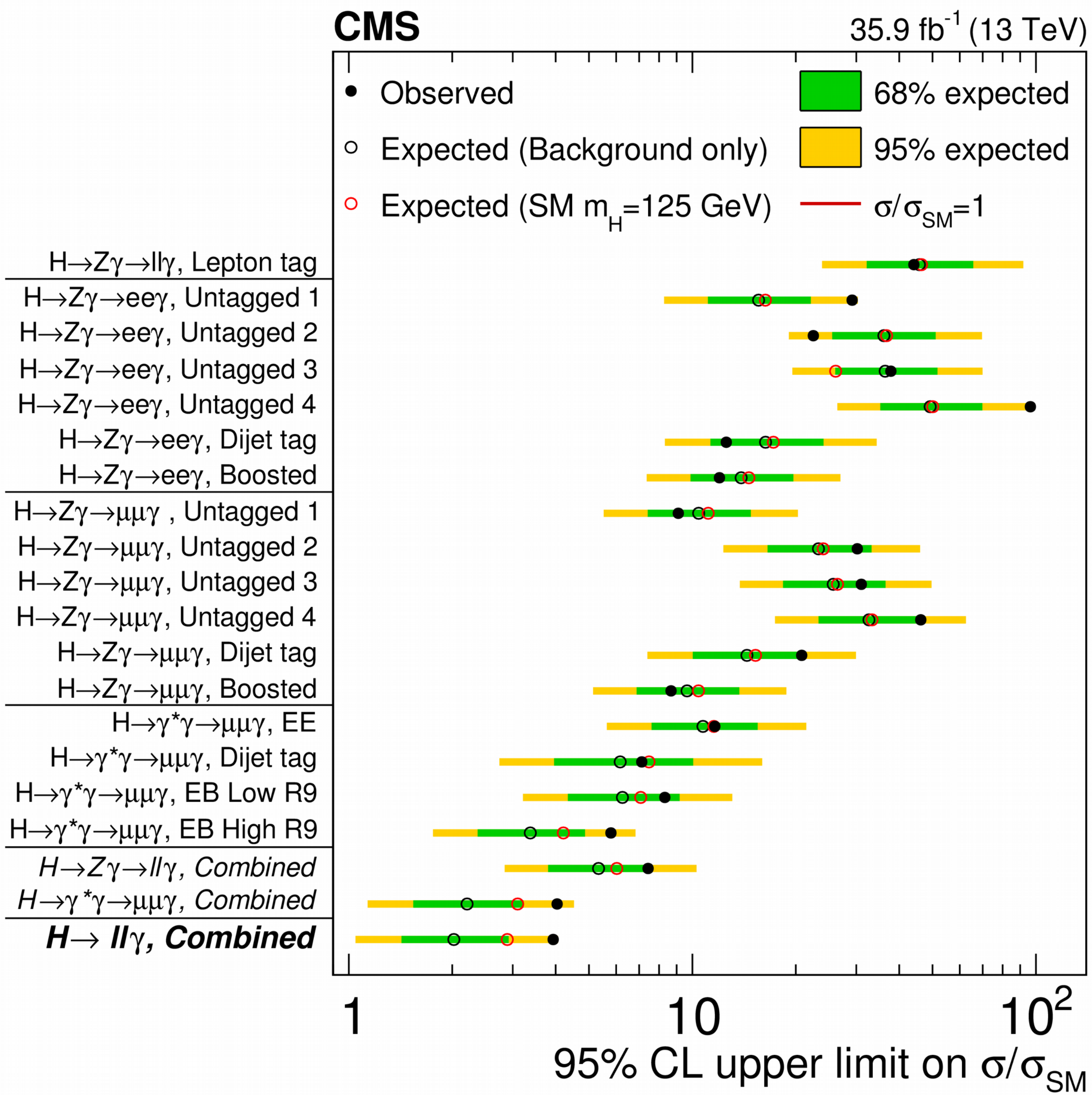
Index	BDT quantile	Max. muon $\|\eta\|$	ggH [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	Signal	Bkg./GeV @125GeV	FWHM [GeV]	Bkg. functional fit form	$S/\sqrt{B}$ @ FWHM
0	0 – 8%	$\|\eta\| < 2.4$	4.9	1.3	3.3	6.3	31.9	21.2	3150.5	4.2	mBW $\cdot B_{deg4}$	0.12
1	8 – 39%	$1.9 < \|\eta\| < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1327.5	7.3	mBW $\cdot B_{deg4}$	0.16
2	8 – 39%	$0.9 < \|\eta\| < 1.9$	10.3	2.8	6.5	6.4	5.2	41.1	2222.2	4.1	mBW $\cdot B_{deg4}$	0.29
3	8 – 39%	$\|\eta\| < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	775.9	2.9	mBW $\cdot B_{deg4}$	0.17
4	39 – 61%	$1.9 < \|\eta\| < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	435.0	7.0	mBW $\cdot B_{deg4}$	0.14
5	39 – 61%	$0.9 < \|\eta\| < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	955.9	4.1	mBW $\cdot B_{deg4}$	0.31
6	39 – 61%	$\|\eta\| < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	479.3	2.8	mBW $\cdot B_{deg4}$	0.26
7	61 – 76%	$1.9 < \|\eta\| < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	146.6	7.6	mBW $\cdot B_{deg4}$	0.11
8	61 – 76%	$0.9 < \|\eta\| < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	514.3	4.2	mBW $\cdot B_{deg4}$	0.29
9	61 – 76%	$\|\eta\| < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	319.7	3.0	mBW	0.28
10	76 – 91%	$1.9 < \|\eta\| < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	102.4	7.2	Sum Exp(n=2)	0.14
11	76 – 91%	$0.9 < \|\eta\| < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	363.3	4.2	mBW	0.34
12	76 – 91%	$\|\eta\| < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	230.0	3.2	mBW $\cdot B_{deg4}$	0.34
13	91 – 95%	$\|\eta\| < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	95.5	4.0	mBW	0.28
14	95 – 100%	$\|\eta\| < 2.4$	2.0	19.4	1.5	1.4	0.7	13.7	82.4	4.2	mBW	0.47
overall			59.1	61.1	51.8	52.3	49.2	253.3	12 961.5	3.9		

H→μμ



5.0 fb-1 (7 TeV) + 19.8 fb-1 (8 TeV) + 35.9 fb-1 (13 TeV)
CMS
Observed
Expected (background, 68% CL, 95% CL)
Expected (SM mH = 125 GeV)
95% CL Limit on σ/σSM
mH [GeV]
0
1
2
3
4
5
6
7
120
121
122
123
124
125
126
127
128
129
130

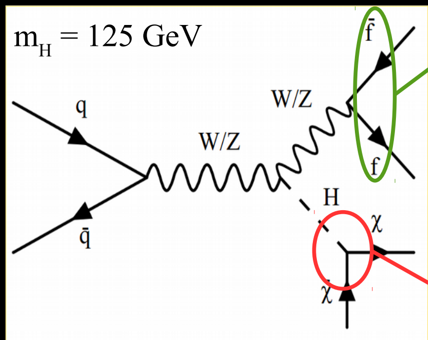
H→ℓℓγ



CMS
35.9 fb-1 (13 TeV)
Observed
Expected (Background only)
Expected (SM mH=125 GeV)
68% expected
95% expected
σ/σSM=1
H→Zγ→llγ, Lepton tag
H→Zγ→eeγ, Untagged 1
H→Zγ→eeγ, Untagged 2
H→Zγ→eeγ, Untagged 3
H→Zγ→eeγ, Untagged 4
H→Zγ→eeγ, Dijet tag
H→Zγ→eeγ, Boosted
H→Zγ→μμγ , Untagged 1
H→Zγ→μμγ, Untagged 2
H→Zγ→μμγ, Untagged 3
H→Zγ→μμγ, Untagged 4
H→Zγ→μμγ, Dijet tag
H→Zγ→μμγ, Boosted
H→γ*γ→μμγ, EE
H→γ*γ→μμγ, Dijet tag
H→γ*γ→μμγ, EB Low R9
H→γ*γ→μμγ, EB High R9
H→Zγ→llγ, Combined
H→γ*γ→μμγ, Combined
H→ llγ, Combined
1
10
10^2
95% CL upper limit on σ/σSM

Higgs decay to invisible

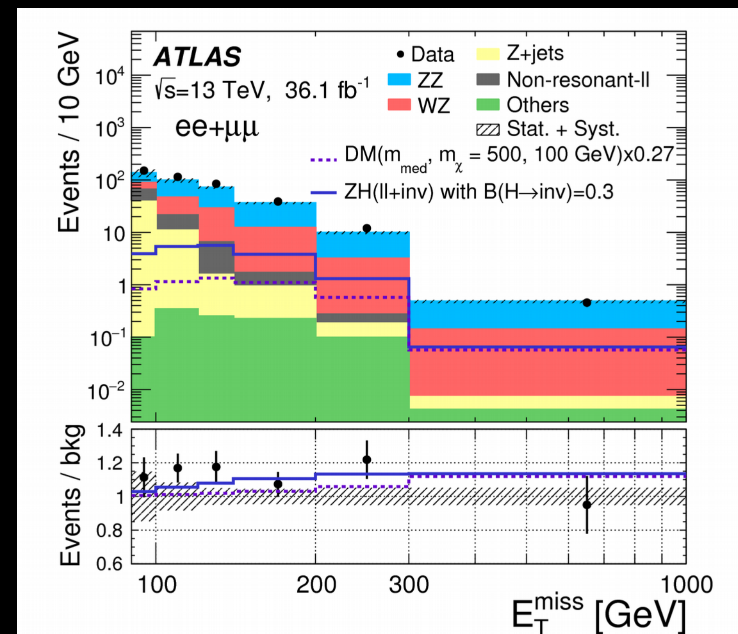
Phys. Lett. B 776 (2017) 318



A pair of leptons with $m_{\ell\ell} \sim m_Z$

Relatively large E_T^{miss}

➡ Fit to E_T^{miss} distribution

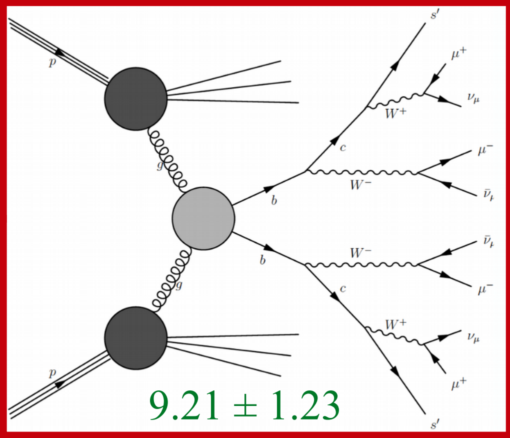


Backgrounds

- ZZ taken from simulation, including uncertainties (10%)
  - Not enough statistics in 4ℓ data control region
- WZ scaled by a data-driven factor, 1.29, from a 3ℓ control region
- Z+jets from data using the so-called ABCD method based on E_T^{miss} and the event topology
- Non-resonant-ℓℓ from eμ data

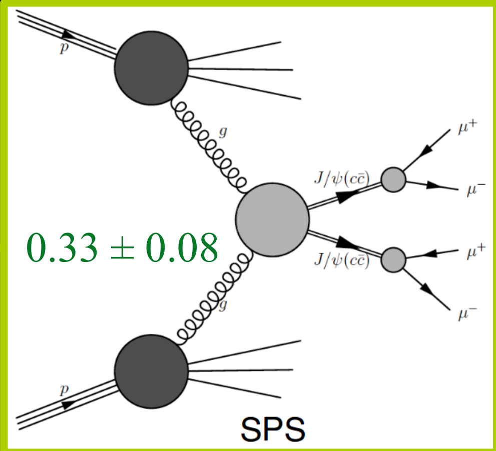
Backgrounds

- Events with == 3μ → 1 dimuon
- Two $m_{\mu\mu}$ templates:
  - Dimuon with or w/o high-p_T muon
- $S(\mu\mu_{1,}\mu\mu_2) = \alpha.S(\mu\mu_{hp})\times S(\mu\mu_{hp}) + (1-\alpha).S(\mu\mu_{hp})\times S(\mu\mu_{lp})$
  - ➔ Normalized
  - A_D/A_{OD} used to interpolate from all range into corridor

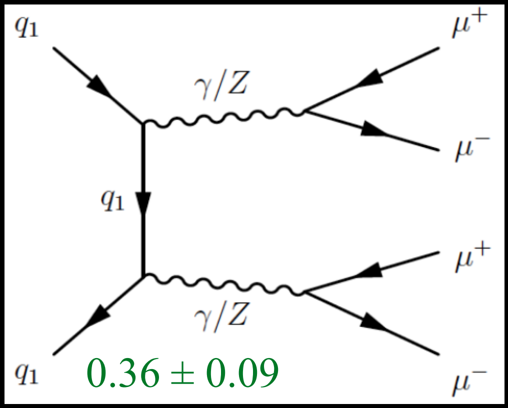


From data

- Selected using B-physics trigger, ==2 dimuons
- Random muon pairing, each compatible with J/ψ mass
- The non-prompt contribution is subtracted (ABCD method for $I_{\mu\mu}$'s)
- SPS and DPS cont. estimated with template fit of $\Delta y_{\mu\mu 1,\mu\mu 2}$
- The data/MC is applied on MC in signal region



From data



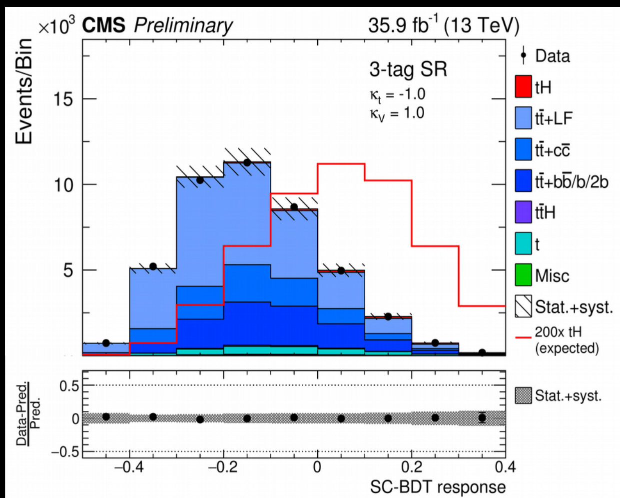
From MC

Inverted top-H coupling: tHq search

CMS-HIG-18-009

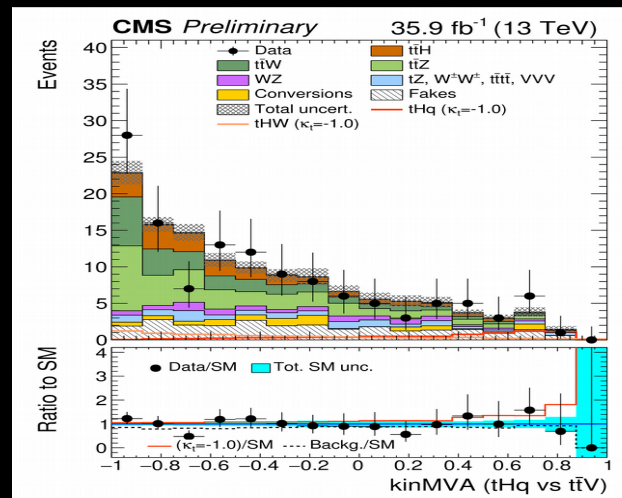
Three analysis are combined

H→ $b\bar{b}$ (HIG-17-016)



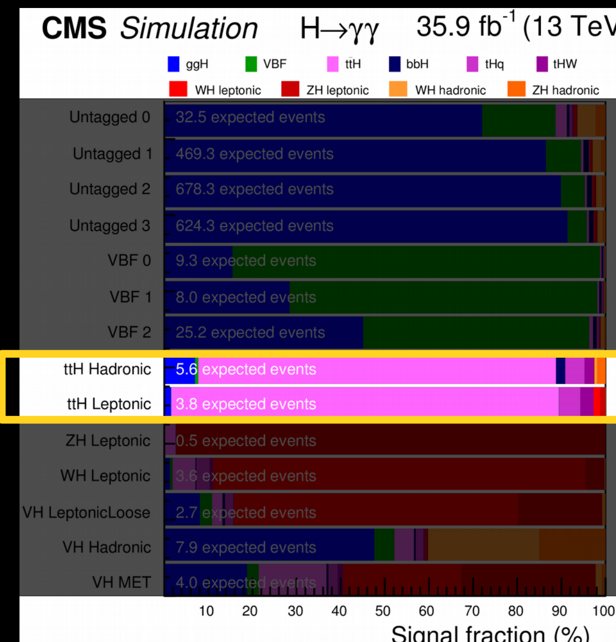
- Signal: κ_t = -1
- Leptonic top decay
- Categories: 3 & 4 b-jets
- BDT's for jet assignments
- BDT's against backgrounds
  - ➔ Simultaneous fit in all regions

Multi-lepton H→ WW/ZZ/ττ (HIG-17-005)



- Signal: κ_t = -1
- 3ℓ and same-sign 2ℓ
- BDT trained against $t\bar{t}V$
- BDT trained against $t\bar{t}$
- Merged in one BDT with optimized binning

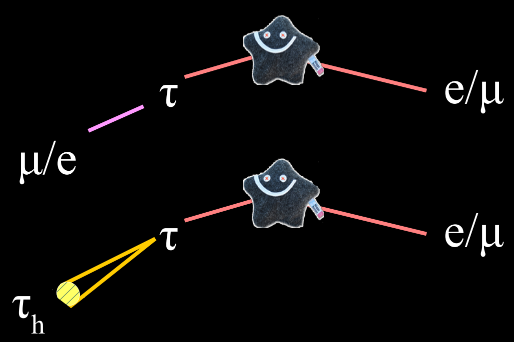
H→ γγ (arXiv:1804.02716)



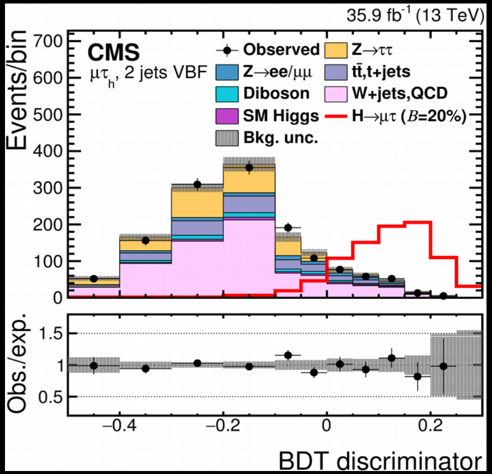
- $t\bar{t}H$ categories from H→ γγ measurement
- Signal efficiency and acceptance evaluated for κ_t = -1

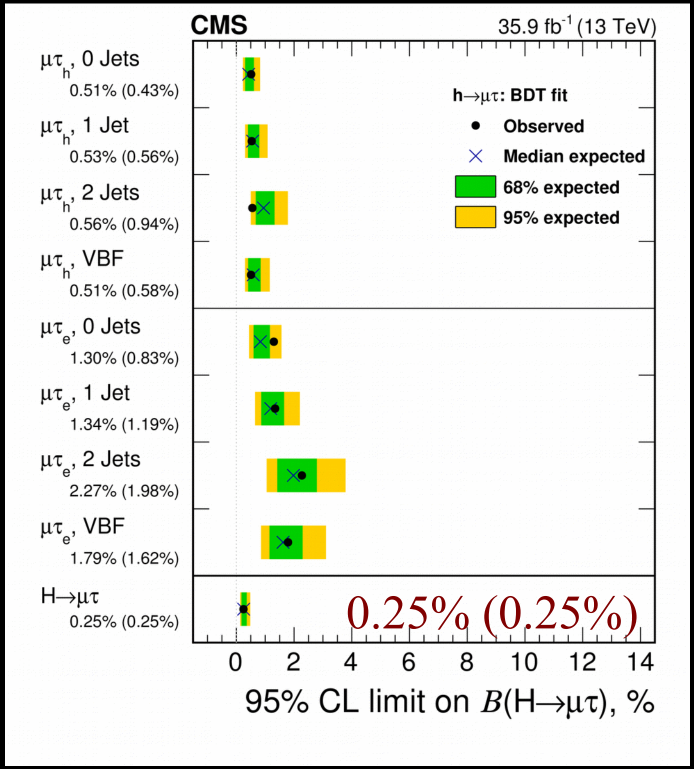
Lepton Flavor Violating Higgs decays

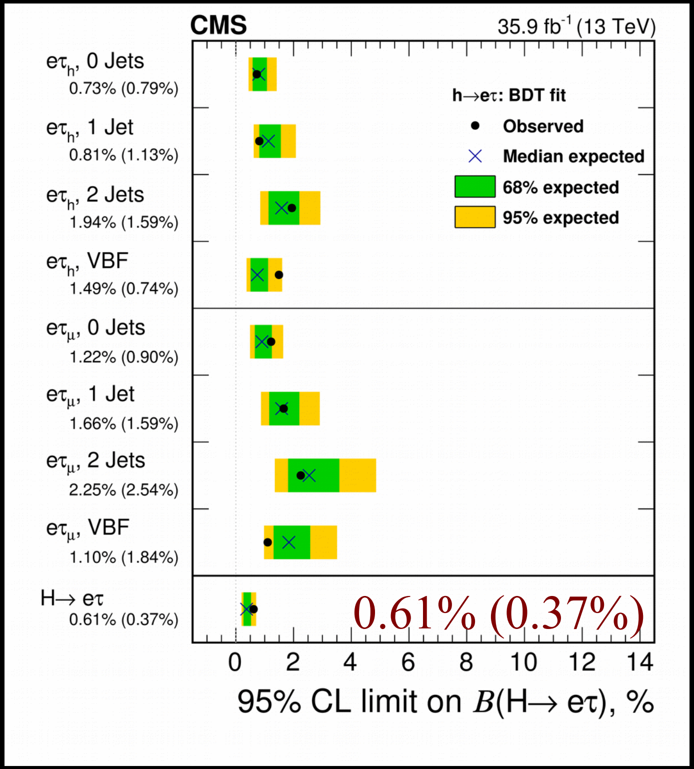
JHEP 06 (2018) 001



- ggH and VBF productions
- Lepton selection
- Categories: number of jets (0,1,2) and m_{jj}
- BDT trained in all categories
- Bkgs from/corrected with data







Lepton Flavor Violating Higgs decays

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